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Resources and environmental management for green development

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Published in
Frontiers in Environmental Science

ISSN 1664-8714
ISBN 978-2-8325-4457-0
DOI 10.3389/978-2-8325-4457-0

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Resources and environmental management for green development

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Citation
Zhang, F., Chuai, X., Gao, L., eds. (2024). *Resources and environmental management for green development*. Lausanne: Frontiers Media SA.
doi: 10.3389/978-2-8325-4457-0

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frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 28 September 2022
DOI 10.3389/fenvs.2022.1012856

OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to
Environmental Economics and
Management,
a section of the journal
Frontiers in Environmental Science

RECEIVED 06 August 2022
ACCEPTED 29 August 2022
PUBLISHED 28 September 2022

CITATION
Wang C, Zheng Q, Zeng H, Wu Y and Wei C (2022), What configurational conditions promote tourism eco-transformation? a fuzzy-set qualitative comparative analysis based on the TOE framework.
Front. Environ. Sci. 10:1012856.
doi: 10.3389/fenvs.2022.1012856

What configurational conditions promote tourism eco-transformation? a fuzzy-set qualitative comparative analysis based on the TOE framework

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Tourism eco-transformation can provide a long-lasting competitive advantage. However, successful transformation is a challenge for both academia and industry. The literature has focused on the net effect of a single factor. Still, we build on the Technology-Organization-Environment framework and propose that tourism eco-transformation does not depend on a single condition but the configurational effect of organization, environment, and technology. We found six conditions that influence eco-transformation in Chinese provinces. The results show that 1) the tourism eco-transformation in China from 2016 to 2019 “declines first and then rises,” indicating a “U” shape. Spatial distribution is stable; 2) We can classify the high-level transformation model into four configurational types: technology-pulling organization, proactive organization, environmental stress organization, and comprehensive organization. Not-high-level transformation model can be categorized as comprehensive absence and respectable; 3) There are three critical conditions for tourism external connections, environmental regulation, and tourism ecology promotion. In contrast, digital information level, technology innovation capability, and tourism resource endowment are largely determined based on the specific situation. We explore high-level and not-high-level configurational paths of tourism eco-transformation and gain new theoretical insights. We also guide tourism managers to choose or modify high-level tourism eco-transformation paths based on local characteristics to avoid not-high-level tourism eco-transformation situations.

KEYWORDS

TOE, configurational effect, tourism eco-efficiency, tourism eco-transformation, fsQCA, super-EBM

1 Introduction

Tourism's rapid growth has increased carbon emissions (Lenzen et al., 2018), and the climate crisis is driving tourism eco-transformation (Scott and Gössling, 2022). Travel & Tourism Council (2015) stresses the importance of integrating climate change into development strategies for a low-carbon economy. Tourism eco-transformation (TET) is a common challenge faced by attractions worldwide. Researchers have found that eco-transformation increases regional tourism competitiveness (Rodríguez-Díaz and Pulido-Fernández, 2020) and promotes innovation in tourism enterprises (Pikkemaat et al., 2019). However, TET is still in its infancy (Gössling et al., 2013; Darvishmotevali et al., 2020; Ruan et al., 2022).

Tourism is a complex phenomenon and is considered an integrated adaptive system (McDonald, 2009; Baggio et al., 2010). It consists of interrelated subjects. These subjects learn, adapt, and evolve according to internal and external conditions (Schianetz et al., 2007). TET is part of the tourism system and represents a shift in its behavior (Rastegar, 2022). As a result, tourism environmental performance is enhanced through synergistic interaction between stakeholders in the governance process (Franzoni, 2015; Herrero et al., 2022). The TET process is complex, non-linear, and dynamic (Goeldner and Ritchie, 2007). Local governments often use tourism policies to promote TET (Suno Wu et al., 2021), but they are also affected by multiple external influences, including changes in social, economic, and political environments (Farsari et al., 2011). Meanwhile, the non-linear relationship between TET entities leads to a form of synergy that makes the whole better than the sum of its parts (McDonald, 2009). Furthermore, TET is a plastic concept (Schianetz et al., 2007), making it difficult to understand and implement.

Nevertheless, scholars have explored the influence mechanisms of TET from different perspectives, including environment-led, organization-led, and technology-led. Some scholars believe that environmental regulation significantly impacts TET (Chen et al., 2021; Zha et al., 2021). Chen et al. (2021) demonstrate that environmental regulation can suppress tourism carbon emissions, promote industrial structure upgrading, and promote TET. Scholars have pointed out the impact of technological conditions on TET. Increasing digital information levels reduces information asymmetry and facilitates TET by easing access to information between subjects (Hadjielias et al., 2022; Wang et al., 2022). In the face of environmental and technological uncertainty, technology innovation capability reduces perceived risk and improves resource efficiency (Sarpong et al., 2022). Most scholars believe that environmental regulation and technological conditions indirectly contribute to TET, while tourism organizations promote it directly. Governments enhance tourism endowments, optimize tourism structures, and improve resource allocation efficiency through rational planning (Gunn and Var, 2020).

Meanwhile, managers reach out to neighboring provinces to enhance tourism resources by forming strategic alliances with them (Pham et al., 2021). Accordingly, tourism ecology promotion has been widely adopted by tourism authorities. Losada and Mota (2019) Nieves describes the practice of the Municipality of the Douro of filming "slow tourism". The net effect of a single variable on TET has been examined from various perspectives. But since TET is a complex phenomenon, explaining its complex impact mechanisms seems more significant. An important consideration is to examine variable relationships from a configurational perspective.

Based on these findings, we concluded that the research gaps in TET might be as follows: First, scholars acknowledge that TET is a complex system engineering and have explored the influence mechanisms driving TET from various perspectives. Many studies, however, have focused only on examining the net effect of a single variable on TET rather than considering the configurational effect of the conditional variables. Second, scholars seem interested in studying the mechanisms that drive TET but have paid little attention to how combinations of conditional variables may hinder it. Ragin (2008) states, "In management research, avoiding negative outcomes and promoting positive outcomes are both important". It leads us to ask: what configurational conditions promote and hinder TET?

We developed the TOE (Technology-Organization-Environment) framework to analyze TET based on the existing literature. This framework includes the environmental dimension (environmental regulation), the technological dimension (digital information level, technology innovation capability), and the organizational dimension (tourism external connections, tourism resource endowment, tourism ecology promotion). To further explore the influence mechanism of TET, we used fuzzy set qualitative comparative analysis (fsQCA) based on a configurational perspective. fsQCA assumes that the prior conditions interact rather than are independent (Ragin, 2008; Fiss, 2011; Pappas and Woodside, 2021). By focusing on the configurational effects of the prior conditions, we can better understand the causal mechanisms of TET. fsQCA also allows for multiple analytical possibilities (Pappas and Woodside, 2021). It can test several configurations associated with the same outcome for adequacy. So, We can use it to reveal the types and paths of TET and analyze the causal asymmetry between high-level and not-high-level of TET. Undesired output Super-EBM and Getis-Ord Gi* were also used in our research. The former measures the level of TET. In contrast, the latter aims to characterize the spatial distribution of TET.

Our study may contribute to the following: 1) We propose a comprehensive analytical framework for TET. 2) We reveal multiple paths that lead to high-level and not-high-level TET and provide evidence against "one-size-fits-all" tourism land management. 3) We propose an alternative approach to determining tourism performance: "Super-EBM + fsQCA." It allows us to investigate the complex causal relationships between conditions and tourism performance.

2 Literature review

2.1 Tourism eco-transformation

TET has not yet formed a unified concept, focusing on Strategic Faction (Pan et al., 2018) and Innovation Faction (Bramwell and Lane, 2012). The Strategic Faction focuses on policy, regulation, and management (Urry, 2005); the Innovation Faction concentrates on products and services, management, and technological innovation (Bramwell and Lane, 2012). In this paper, TET is the goal of the tourism government to guide stakeholders to carry out eco-innovation (technology innovation, management innovation) to realize the transformation from rough tourism development mode to intensive tourism development mode, expressed explicitly as the improvement of tourism performance.

TET has a multi-level positive impact on tourism sites. Due to the climate crisis, scholars are increasingly concerned about tourism's carbon emissions (Lenzen et al., 2018; Scott and Gössling, 2022). At the macro level of analysis, TET curbs carbon emissions. Local governments often develop policy frameworks to achieve TET (Suno Wu et al., 2021). Tourism destinations can reduce carbon footprints with effective destination carbon management (Gössling et al., 2015). As tourism destinations get more competitive, TET is seen as a way to increase their competitiveness (Capacci et al., 2015; Goffi et al., 2019; Kuo et al., 2022). Capacci et al. (2015) points out that "Blue Flags" (one of the eco-labels) open up an environmental niche. It has increased the flow of tourism to the Italian Riviera and improved competitiveness. According to Goffi, sustainable tourism can boost competitiveness in developing countries (Goffi et al., 2019). On a micro-level analysis, TET improves the environmental performance of hotel companies. In Andalusian hotels, García-Pozo et al. (2016) shows that eco-innovation practices increase labor productivity; Aboelmaged (2018) concludes that environmental orientation and eco-innovation together contribute to hotel performance. As a result, TET could positively impact tourist destinations and businesses.

According to the PDCA (Plan-Do-Check-Action) principle, Tourism Performance Evaluation is vital in managing tourism sites (Herrero et al., 2022). Several approaches have been used to characterize tourism performance evaluation, including the life cycle approach (Herrero et al., 2022), the dynamic stochastic Frontier model (Assaf and Tsionas, 2015), and tourism eco-efficiency (Gössling et al., 2005). Tourism eco-efficiency reflects how the economy and the environment interact. In addition, it is easy to use, making it a good tool for assessing tourism performance (Peng et al., 2017; Sun and Hou, 2021). Peng et al. (2017) measures Huangshan Park's eco-efficiency over four periods; Zha et al. (2021) measures Chinese tourism's eco-efficiency from 2005 to 2015. We also used tourism eco-efficiency to characterize TET.

Even so, how TET is achieved is unclear (Gössling et al., 2013). TET involves multiple stakeholders (Buckley, 2012), such as local tourism governments (Bramwell and Lane, 2010), businesses (Pan et al., 2018), and tourists (Lin et al., 2022), and requires a comprehensive weighing of public and private interest objectives. Moreover, TET is non-linear and emergent, making it even harder to implement. There are two main paths of implementation: the government-led path and the enterprise-led path. Tourism companies often use eco-label and digital technologies to achieve transformation (Botero and Zielinski, 2020; Herrero et al., 2022). However, scholars are more likely to recommend macro-regulation by local tourism governments to assist enterprises' transformation. TET needs authorities to provide policies and planning procedures to support and manage tourism (Bramwell and Lane, 2012). Poor government leadership on Danish beaches has contributed to tourists' lack of ecological awareness (Andersen et al., 2018). Despite the non-linear nature of TET, scholars have not figured out how to promote it. We need to examine mechanisms from a holistic perspective.

2.2 Theoretical model: Technology-Organization-Environment framework and tourism eco-transformation

TOE was proposed by Tornatzky (Tornatzky et al., 1990) and applied to explain how organizations adopt green technology. (Zhang et al., 2020). Scholars consider eco-innovation to be an essential path for TET (Alegre and Berbegal-Mirabent, 2016; Sakdiyakorn and Sivarak, 2016), including Technology Innovation (Fuchs et al., 2010) and Management Innovation (Del Chiappa and Baggio, 2015). Resource Dependence Theory suggests that TET requires critical conditions. We introduce the TOE framework to the field of TET, exploring the configurational effect of conditions between organization, environment, and technology.

2.2.1 Technical conditions

2.2.1.1 Digital information level

Digital information level is an essential tool to improve tourism environmental performance (Peng et al., 2017; Shu et al., 2022) and promote tourism towards sustainability (Filipiak et al., 2020). Information theory holds that digital technology development can reduce information asymmetry between tourists, businesses, and tourism authorities (Wang et al., 2022) and enhance the strategic agility of organizations (Hadjielias et al., 2022). Wang et al (2022) argues that digital finance can improve resource allocation efficiency by increasing tourism demand and promoting tourism entrepreneurship.

Hadjielias et al. (2022) further explained that digital technology could enhance tourism organizations' strategic agility, including customer, partnering, and operational agility. In terms of value creation, the digital information level is conducive to changing digital consumer behavior, unlocking potential markets, and increasing tourism infrastructure utilization. Hadjielias et al. (2022) also believes that digital technology can create value in delivery. Marques and Borba (2017) sees digital information technology significantly influencing creative urban tourism. Additionally, Talwar et al. (2022) noted that digital information facilitates tourists' acceptance of virtual reality as sustainable tourism. Therefore, we consider environmental regulation to be one of the conditions for TET.

2.2.1.2 Technology innovation capability

Technology innovation capability means the potential of a region to create and transfer knowledge (Loureiro and Nascimento, 2021). Successful transformation requires that tourism governments rely on knowledge stores to face the problems associated with technological uncertainty and environmental uncertainty. It reduces perceived risk for tourism governments and businesses (Verreynne et al., 2019; Sarpong et al., 2022). It is reflected in reduced seasonal fluctuations in tourism and improved organizational performance (Martín et al., 2014; Bhat and Sharma, 2022). Puertas Medina et al. (2022) studied the accommodation sector from 2015–2019 in the Spanish coastal region. She found the ability to innovate with technology effectively reduced seasonal fluctuations in the accommodation sector and thus achieved higher efficiency levels. Bhat and Sharma (2022) points out that hospitality's technological innovation is directly related to corporate environmental performance. In the Yangtze River Delta, Gan demonstrates that technical innovation capacity positively impacts sustainable tourism development. This relationship, however, varies by region (Gan et al., 2022). Therefore, we believe that technological innovation capability is one of the conditions for TET.

2.2.2 Organizational conditions

2.2.2.1 Tourism ecology promotion

Local tourism governments widely adopt tourism ecology promotion as a form of social marketing due to its "low cost and quick results" (Losada and Mota, 2019; Tkaczynski et al., 2020). In implementing the tourism ecology promotion strategy, local authorities are fulfilling the green aspirations of tourists and residents (Nistoreanu et al., 2020) and raising environmental awareness in tourist areas. Therefore, ecology promotion promotes pro-environmental behavior (Tkaczynski et al., 2020) and enhances customer loyalty (Cai et al., 2021). In addition, green tourism images can motivate green tourism behavior (Line et al., 2017). Specifically, Losada and Mota (2019) notes that the Municipality of Douro promotes sustainability through the filming of 'slow tourism,' and Minoli et al. (2015) points out that using Eco-labels by tourist authorities increases competitiveness. Cai et al. (2021) believes green B&B promotion strategies can increase tourist loyalty. Therefore, we believe that tourism ecology promotion is one of the conditions for TET.

2.2.2.2 Tourism external connections

Tourism external connections indicate the exchange of material and information flows between tourist destinations. It reflects the extent to which the destination government maintains a cooperative strategy with foreign provinces and municipalities. In social capital theory, external connections can be viewed as resources (Field, 2005). Tourism alliances and community members can provide natural, financial, and human resources on a larger scale through scale economies, knowledge sharing, and marketing collaboration (Pham et al., 2021). In particular, Pham et al. (2021) points out that tourism enterprises can improve their resilience to external shocks by building social networks. Additionally, Kofler et al. (2018) points out that tourism tends to collaborate across segments, which can help them collaborate and innovate. We, therefore, consider tourism external connections to be one of the conditions for TET.

2.2.2.3 Tourism resource endowment

Tourists choose a destination because of its tourism resources (Crouch, 2011). These resources profoundly influence the destination's success in the tourism market (Goeldner and Ritchie, 2007). Governments typically use policies and planning to enhance tourism resource allocation efficiency and achieve resource-intensive development by influencing the quality and quantity of core resources and attractions. Therefore, we believe that tourism resource endowment is one of the conditions for TET.

2.2.3 Environmental conditions

2.2.3.1 Environmental regulation

According to contingency theory, tourism organizations' strategies and actions are influenced by the environment in which they are located (Fernández-Robin et al., 2019). Environmental regulation does not directly affect tourism enterprises. However, it is transmitted through the value chain to the governments and enterprises of tourism places, creating external pressure and indirectly promoting eco-transformation. Scholars have demonstrated the role of environmental regulation in achieving environmental sustainability in tourism (Peng et al., 2017; Kornilaki et al., 2019). Chen et al. (2021) classifies environmental regulation into supervisory management, market incentives, command and control, and public participation, which show different effects on carbon emissions from tourism. High-intensity environmental regulation can also reduce tourism's carbon footprint. Erdoğan et al. (2022) states that improved transportation environmental technologies eliminate the harmful effects of international tourism on environmental quality. We, therefore, consider environmental regulation as one of the conditions for tourism TET.

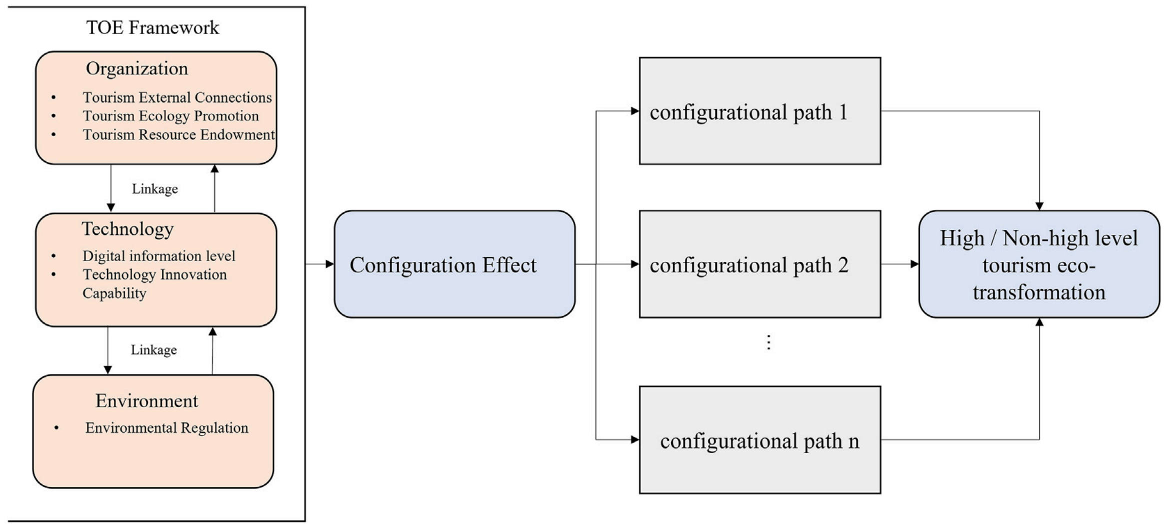

FIGURE 1
TET configurational framework.

2.3 Configurational framework

TET has been examined from multiple perspectives, but research has generally focused on the net effect of a single factor. Accordingly, we explore the influence mechanism from a configuration perspective. The TOE configurational framework is developed, and we argue that TET depends on environmental, organizational, and technological factors acting together. The theoretical model is shown in Figure 1.

3 Methodology

3.1 Research method

3.1.1 Super-EBM model

Assume that the determination of TET has $k = 1, ..., K$ Decision Making Units (DMU), DMU k input I factors x_i (i = 1, ..., I), producing N desired outputs y_n (n = 1, ..., N) and Z undesired outputs y_n (n = 1, ..., N) and Z undesired outputs b_z (z = 1, ..., Z). Pastor and Lovell (2005) proposed a global reference method that enables inter-period comparability of efficiency or inefficiency of the same decision unit and avoids the phenomenon of no feasible solution. The global reference TET possibility set PPS (Production Possibilities Set) is as follows.

$$PPS^T \left\{ \begin{array}{l} (x^t, y^t, b^t) \mid \sum_{t=1}^{T}\sum_{j=1}^{K}\lambda_j^t x_{ji}^t \leqslant x_i^t; \sum_{t=1}^{T}\sum_{j=1}^{K}\lambda_j^t x_{jn}^t \geqslant y_n^t \\ \sum_{t=1}^{T}\sum_{j=1}^{K}\lambda_j^t b_{jz}^t \leqslant b_z^t; \sum_{t=1}^{T}\sum_{j=1}^{K}\lambda_j^t = 1; \lambda \geqslant 0 \end{array} \right\} \quad (1)$$

Where: (x_t, y_t, b_t) denotes the optimal solution of the model; x_{ji}^t, y_{jn}^t, b_{jz}^tdenotes the ith input factor, the nth desired output, and the zth undesired output of the jth decision unit, respectively.x_i^t, y_n^t, $b_z^t$is greater than 0. λ_j^t denotes the weight, and increasing the constraint of λ = 1 indicates Variable Return-to-Scale (VRS), and removing the constraint of λ = 1 The constraint of removing λ = 1 indicates Constant Return-to-Scale (CRS).

We choose the CRS hypothesis considering that the factors of production, such as tourism fixed assets in a particular province, will not change significantly. Under the CRS assumption, the global reference undesired super epsilon-based measure (Super-EBM) efficiency measure model with the following equation.

$$\begin{aligned} &\gamma^* = \min \frac{\theta - \varepsilon_x \sum_{i=1}^{m} \frac{\omega_i^- s_i^-}{x_{ik}}}{\varphi + \varepsilon_y \sum_{r=1}^{s} \frac{\omega_r^+ s_r^+}{y_{rk}} + \varepsilon_b \sum_{t=1}^{p} \frac{\omega_t^{b-} s_t^{b-}}{b_{tk}}} \\ &\text{s.t.} \sum_{j=1}^{n} x_{ij}\lambda_j + s_i^- = \theta x_{ik}, i = 1, \ldots m \\ &\sum_{j=1}^{n} y_{rj}\lambda_j - s_r^+ = \varphi y_{rk}, r = 1, \ldots s \\ &\sum_{j=1}^{n} b_{tj}\lambda_j + s_t^{b-} = \varphi b_{tk}, t = 1, \ldots p \\ &\lambda_j \geq 0, s_i^-, s_r^+, s_t^{b-} \geq 0 \end{aligned} \quad (2)$$

where it is assumed that there are n decision units DMU_j (j = 1,2,...,n); each DMU_j has m inputs x_{ij} (i = 1,2,...,m); s desired outputs y_{rj} (r = 1,2,...,s); p undesired output b_{tj} (t = 1,2,...,p); λ is the linear combination coefficient of DMU; x_{ik}, y_{rk} and b_{tk} are the input, desired output and undesired output of DMU_j to be measured, respectively. s_i^-, s_r^+, s_t^{b-} are the relaxation amounts of the i-th input, the r-th desired output and the t-th undesired output, respectively; $\omega_i^-, \omega_r^+, \omega_t^{b-}$ are the weights of the i-th input, the r-th desired output and the t-th undesired output indicators, respectively; θ, φ are the efficiency values under the radial condition; ε indicates the importance of the non-radial part in the calculation of efficiency values. γ^* is the result of the efficiency calculation, and the larger value indicates the higher relative efficiency of the decision unit DMU.

3.1.2 Getis-Ord Gi*

Getis-Ord *Gi** can identify high-value and low-value clusters in the spatial region and is used to reveal the spatial distribution pattern of hot and cold regions. Getis-Ord *Gi** index is normalized to Z value. The formula is.

$$Gi^* = \frac{\sum_{j=1}^{n} W_{i,j} - \bar{X}\sum_{j=1}^{n} W_{i,j}}{S\sqrt{\frac{n\sum_{j=1}^{n} W_{i,j} - \left(\sum_{j=1}^{n} W_{i,j}\right)^2}{n-1}}}, \bar{X} = \frac{\sum_{j=1}^{n} X_j}{n}, S = \sqrt{\frac{\sum_{j=1}^{n} X_j^2}{n} - (\bar{X})^2} \quad (3)$$

Where:X is the attribute value of spatial element j; W_i, W_j is the spatial weight between elements i and j; n is the total number of spatial elements; X is the mean value of spatial elements; S is the standard deviation of spatial elements.

3.1.3 fsQCA

fsQCA is a configurational approach based on Set theory and fuzzy algebra (Ragin, 2008) and is suitable for studying complex causal relationships and configurational effects of organizational strategies (Fiss, 2011). We used fsQCA 3.0 (www.compasss.org). The following steps need to be completed: The first stage is data calibration. Specify three essential qualitative anchors (full membership, cross-over point, and full non-membership), with calibration values ranging from [0, 1] to fuzzy fractions; the second stage is necessity analysis. fsQCA utilizes Boolean algebra, which estimates indexes of consistency and coverage to analyze the necessity. For the necessity analysis, the consistency index is based on the following formula (Ragin, 2008):

$$Consistency\,(X_i \geq Y_i) = \frac{\sum[\min(X_i, Y_i)]}{\sum(Y_i)} \quad (4)$$

Coverage index is calculated as follows (Ragin, 2008):

$$Coverage\,(X_i \geq Y_i) = \frac{\sum[\min(X_i, Y_i)]}{\sum(X_i)} \quad (5)$$

Where: X_i is the calibrated antecedent condition, and Y_i is the calibrated outcome condition for unit i.

The third stage is the construction of the truth table. The truth table provides all the logical configurations. The number of rows retained depends on the consistency cutoff and frequency threshold. Finally, the configurations are determined by using Boolean minimization and the Quine-McCluskey algorithm. Ragin (2008) defines the corresponding consistency and coverage indexes for sufficiency analysis as follows.

$$Consistency\,(X_i \leq Y_i) = \frac{\sum[\min(X_i, Y_i)]}{\sum(X_i)} \quad (6)$$

$$Coverage\,(X_i \leq Y_i) = \frac{\sum[\min(X_i, Y_i)]}{\sum(Y_i)} \quad (7)$$

Where: X_i is the calibrated antecedent condition, and Y_i is the calibrated outcome condition for unit i.

3.2 Cases

China's government departments are implementing eco-transformation strategies "from the top down." As a "government-guided" tourism industry, China's tourism sector is seeking a TET path, and provinces are already making progress. The degree of transformation in each province is uneven, but the main goal is the same, which satisfies the fsQCA requirement of "maximum similarity" and "maximum heterogeneity" of the cases (Ragin, 2008). To avoid COVID-19 perturbations, we chose 2016–2019 as the research period. To summarize, we selected 30 provinces in China (excluding Hong Kong, Macau, Taiwan, and Tibet) from 2016 to 2019 as cases of TET.

3.3 Indicator selection and description

3.3.1 Tourism eco-transformation

TET describes the transformation of tourism economic activities' production mode (crude growth → intensive growth), expressed as improving tourism environmental performance (Herrero et al., 2022). Therefore, we use tourism eco-efficiency as a proxy variable for TET. Currently, academia does not have a standardized indicator for measuring eco-efficiency. In selecting an indicator, we consider the input-output process of tourism place development, together with available data.

3.3.1.1 Input indicators

Workforce, fixed assets, and land are considered primary factors of production for tourism economic activity (Kapelko and Oude Lansink, 2017). Tourism is a labor-intensive industry. Its economic activity is greatly affected by the workforce. In addition, the accuracy of tourism workforce statistics varies from year to year, which leads to high fluctuations in the data. Therefore, we choose the tertiary sector workforce (Sun and Hou, 2021). Fixed assets are essential for building auxiliary tourism facilities. The fixed assets input is calculated by adding the number of star-rated hotels, the number of travel agencies, and the number of weighted scenic spots (Wang et al., 2020).

TABLE 1 TET input-output indicators and data sources.

Secondary indicators	Specific target	Data resources
Workforce input	Number of the tertiary sector workforce	*China Statistical Yearbook*
Fixed assets input	Number of star-rated hotels	*China Tourism Statistics Yearbook; Provincial Statistical Yearbook*; *Provincial Statistical Bulletin*
	Number of travel agencies	
	Number of weighted scenic spots	
Tourism energy input	Tourism energy consumption	See Supplementary Appendix A1 for details on the author's self-test
Economic benefits	Total Tourism Revenue	*China Tourism Statistics Yearbook*
Social benefits	Total number of visitors received	*China Tourism Statistics Yearbook*
Tourism Carbon Emissions	Tourism Carbon Emissions	See Supplementary Appendix A1 for details on the author's self-test

Another input indicator we selected is tourism energy consumption, a critical component of tourism activities (Nepal et al., 2019). The land indicator, however, was not considered since the tourism satellite account does not include it in its statistics (Zha et al., 2020).

3.3.1.2 Desired output indicators

Tourism aims to satisfy the needs of tourists and create social and economic benefits. Economic benefits are the ideal output indicator. We apply total tourism revenue for representation (Zha et al., 2020). To eliminate the effect of price fluctuations, we use the CPI (Consumer Price Index) and select 2016 as the base year (Peng et al., 2017; Zha et al., 2020). Based on existing literature, we consider the total number of visitors received as a proxy variable for social benefits (Wang and Wang, 2021). Although visitor satisfaction is a desired output indicator, it was not considered due to its various measurement difficulties.

3.3.1.3 Undesired output indicators

Studies have shown that tourism carbon emissions can accurately reflect the impact of tourism development on the ecological environment (Sun, 2016). Thus, tourism carbon emissions are considered undesired output indicators (see Supplementary Appendix A1).

As a result of the above considerations, Workforce, Fixed Assets, and tourism energy consumption are regarded as input indicators, economic benefits and social benefits are regarded as desired output indicators, and tourism carbon emissions are regarded as undesired output indicator (see Table 1).

3.3.2 Technical conditions

Technology innovation capability: We applied the regional innovation capability characterization technology innovation capability from the China Regional Innovation Capability Evaluation Assessment 2019 (https://www.most.gov.cn/zxgz/cxdc/cxdcpjbg/).

Digital information level: We use the China Digital Development Index Report 2019 to represent the digital information level of each province.

3.3.3 Organizational conditions

Tourism external connections: we combine the gravity model with the degree centrality of tourism external connections in social network analysis (See Supplementary Appendix A2 for details on the author's self-test).

Tourism ecology promotion: Baidu indexes assess the government's response to emergencies (Li et al., 2022). We used the Baidu index (https://index.baidu.com/) to indicate tourism ecology promotion efforts. The keywords were "eco-tourism," "low carbon economy," "green consumption," and "sustainable development." "and the period is 2016–2019.

Tourism resource endowment: We draw on existing research and combine World Natural Heritage, World Cultural Heritage, World Heritage - Mixed Property (https://zh.unesco.org/), National AAAAA level tourist attraction (China Tourism Statistics Yearbook), national tourism park of China ("the list of scenic spots and scenic spots issued by the State Council") and National Geopark (http://www.geopark.cn/). We weighted their numbers to characterize tourism resource endowment.

3.3.4 Environmental conditions

Environmental regulation: Salamon (1989) pointed out that it is more comprehensive and objective to measure environmental regulation's intensity in terms of pollution control results. We selected industrial wastewater emissions, industrial SO_2 emissions, and industrial soot emissions (China Statistical Yearbook, Provincial Statistical Yearbook). We weighted these three components to find the environmental regulation levels of different provinces.

4 Results

4.1 Time series analysis of provincial tourism eco-transformation in China

We use a global reference undesired output Super-EBM model to measure TET in Chinese provinces from 2016 to 2019 (see Supplementary Appendix A3). During 2016–2019,

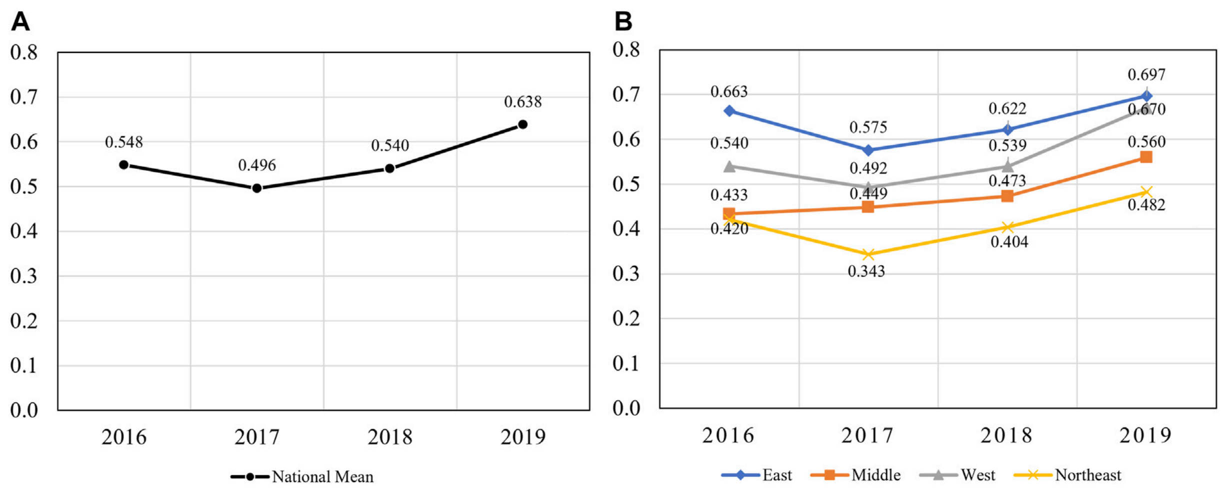

FIGURE 2
TET values of Chinese provinces. Note: **(A)** the average of national TET, **(B)** east, central, west and northeast China, the division is based on (https:// www.stats.gov.cn/ztjc/zthd).

the TET in China showed an upward trend (Figure 2A), increasing from 0.548 in 2016 to 0.638 in 2019, an increase of 16.4%. Specifically, TET decreases initially, then increases, forming a U-shape. The year 2017 represents the turning point. According to the People's Republic of China's National Bureau of Statistics classification criteria, China is divided into Eastern, Central, Western, and Northeastern regions (https:// www.stats.gov.cn/ztjc/zthd). TET growth trends in the east, central, west, and northeast are consistent with the national mean (Figure 2B), which also shows an upward trend. From the spatial distribution analysis, East > West > Central > Northeast. Eastern regions have rich tourism resources, a mature technical structure, and an advanced management model. As a result, TET leads the remaining three regions. Since implementing the western development strategy, the west region's tourism economic structure is becoming more and more reasonable. In addition, dividends appear, and the TET is significantly higher than the center and northeast. Despite the apparent upward trend in the central region, there is still room for improvement. In the northeast, the tourism industry structure needs to be optimized, and workers are leaving, which means the TET is falling behind the other three.

4.2 Spatial distribution of provincial tourism eco-transformation in China

Using Getis-Ord Gi* in ArcGIS10.8, Z-values are divided into cold, sub-cold, sub-hot, and hot regions. Below are the hot and cold spots for TET from 2016–2019. Combining Figure 3, we can see that: 1) From the quantitative analysis, the number of hot points (6→7) and the number of sub-cold provinces (8→9) gradually increase, and the number of cold points tends to decrease (8→6). Moreover, the number of sub-hot points is unchanged (8→8). TET appears to be improving in each province of China, and there is a heightened spatial convergence between provinces. 2) From the analysis of spatial distribution changes, in 2016 and 2019, hot points and sub-cold points are concentrated east of the Hu Line, while cold points are concentrated west of the Hu Line. It indicates that China's geographical environment and tourism economic development have certain zonality, and the regional spatial distribution of TET shows stability and continuity characteristics.

4.3 Antecedent conditions calibration based on fsQCA

Based on existing studies (Hartmann et al., 2022) and considering the characteristics of the case data distribution, we use a direct method for calibration. Quantile values of 75%, 50%, and 25% are used as thresholds for full membership, crossover point, and full non-membership, assuming no singularities. All conditions were calibrated as in Table 2.

4.4 Necessity conditions analysis

Before performing a sufficient solutions analysis, it is necessary to check the necessity of each condition one by one. We combine mainstream fsQCA studies to test whether a single condition (including its non-set) constitutes a necessary condition for high (not-high) TET. When a condition is always present in fsQCA, it becomes the necessary condition of the outcome (Ragin, 2008; Fiss, 2011). The consistency index is used as an essential test for necessity conditions. When the Consistency index is more significant than 0.9,

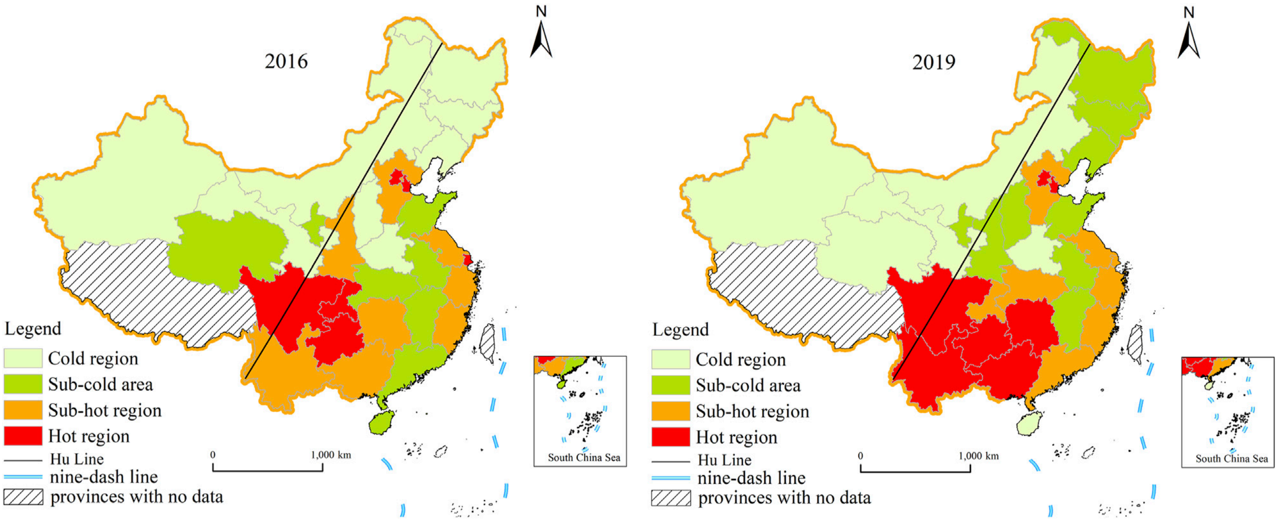

FIGURE 3
Hotspot distribution of the spatial distribution of TET in China. Note: The map is based on the standard map with review number GS (2019) 1697 downloaded from the Ministry of Natural Resources standard map service website, and the base map is unmodified (http://bzdt.ch.mnr.gov.cn/).

TABLE 2 Calibration and Descriptive Statistics of antecedent condition.

Fuzzy set	Calibration			Descriptive statistics			
	Fully In	Crossover	Fully out	Mean	SD	Max	Min
TET	0.539	0.490	0.409	0.484	0.143	0.725	0.183
digital information level	5.803	5.762	5.688	5.781	0.097	6.019	5.648
environmental regulation	3.820	3.583	3.436	3.593	0.338	4.194	2.511
technology innovation capability	3.302	3.135	3.047	3.237	0.304	3.974	2.815
tourism external connections	0.244	0.216	0.188	0.217	0.078	0.394	0.034
tourism resource endowment	2.045	1.934	1.815	1.934	0.301	2.488	0.888
tourism ecology promotion	5.541	5.349	5.167	5.287	0.487	6.083	3.838

the condition is the resulting necessity condition (Ragin, 2008; Fiss, 2011). Table 3 shows the necessity analysis results of high-level and not-high-level of TET analyzed using fsQCA 3.0 software. As seen in Table 3, the level of consistency for all conditions is less than 0.9. Consequently, none of the conditions listed have independent explanatory powers.

4.5 Sufficient solutions analysis

In contrast to necessity analysis, sufficiency analysis examines the sufficiency of results generated by multiple configurational conditions. Sufficient solutions analysis involves the analysis of true tables. Its purpose is to examine cases with specific condition combinations and assess whether they lead to the same results (Ragin, 2008). The true table lists all possible combinations of conditions. Our study involves 6 antecedent conditions, so there are 64 possible combinations (i.e., 2^6). We identify all combinations of conditions with at least 1 case to reduce the true table. Setting case cutoff to 1 is recommended for medium samples (Schneider and Wagemann, 2012). Then, we set the consistency cutoff to reduce the true table further. We employ 0.8 as the consistency cutoff, which is higher than the recommended value of 0.75 (Ragin, 2008). We set the PRI (Proportional Reduction in Inconsistency) to 0.7 to reduce the contradictory relationship between configurational conditions. It is higher than the 0.5 suggested by Greckhamer (Greckhamer et al., 2018). Supplementary Appendices 4A, 4B provide details about the

TABLE 3 Necessity analysis of single conditions.

Condition	High-level of TET		Not-high-level of TET	
	Consistency	Coverage	Consistency	Coverage
digital information level	0.699	0.687	0.460	0.406
~ digital information level	0.396	0.449	0.646	0.658
environmental regulation	0.655	0.698	0.437	0.418
~ environmental regulation	0.454	0.473	0.685	0.641
technology innovation capability	0.684	0.682	0.488	0.437
~ technology innovation capability	0.435	0.486	0.644	0.647
tourism external connections	0.804	0.760	0.405	0.344
~ tourism external connections	0.307	0.365	0.718	0.767
tourism resource endowment	0.672	0.658	0.486	0.427
~ tourism resource endowment	0.415	0.473	0.611	0.626
tourism ecology promotion	0.692	0.690	0.436	0.391
~ tourism ecology promotion	0.389	0.434	0.654	0.656

Note: ~ means Not-high (logical operator).

TABLE 4 Configurational conditions strongly related to TET.

Antecedent condition	High-level of TET						Not-high-level of TET		
	H1	H2	H3	H4	H5	H6	L1	L2	L3
DIL	●		⊗	●	●		⊗	⊗	
TIC	●	⊗	⊗	●	●			⊗	●
ER		⊗	●	●	●	●	⊗	⊗	⊗
TEC	●	●	●		●	●	⊗	⊗	⊗
TRE	⊗	●	⊗	●		●	⊗		⊗
TEP	⊗	●	●	●	●		⊗	⊗	⊗
consistency	1	0.965	0.815	0.951	0.962	0.919	0.977	1	1
coverage	0.121	0.153	0.115	0.352	0.349	0.317	0.259	0.207	0.252
unique coverage	0.046	0.085	0.051	0.057	0.041	0.012	0.087	0.035	0.063
Solution coverage				0.615				0.399	
Solution consistency				0.913				0.981	
Typical cases	Tianjin, Sichuan	Yunnan, Fujian	Guangxi	Zhejiang, Guangdong, Jiangsu, Beijing, Sichuan	Jiangsu, Zhejiang, Beijing, Chongqing, Sichuan	Jiangsu, Zhejiang, Beijing, Sichuan, Hunan	Heilongjiang, Ningxia	Ningxia, Xinjiang	Hainan, Qinghai

Note: ● indicates the condition exists, ⊗ indicates the condition is missing, blank space indicates that the presence or absence of the condition does not affect the result

True table. Finally, we use Boolean minimization and the Quine-McCluskey algorithm to determine configurational conditions.

As shown in Table 4, the consistency of any configurational condition is above the threshold value of 0.8. The high-level of configurational condition solution consistency is higher than 0.9.

These conditions constitute sufficient explanations for TET. Further, coverage refers to the explanatory power of the configurational condition, which reflects the empirical relevance or importance of the configuration (Ragin, 2008). It is similar to R-square in regression (Fiss, 2011). In our study, six configurations explained 61.5% of the cases. Based on the not-high-level configurational conditions, solution consistency was 0.981, and solution coverage was 39.9%. For the convenience of writing, we use the abbreviations of 6 conditions to represent (digital information level (DIL); technology innovation capability (TIC); environmental regulation (ER); tourism external connections (TEC); tourism resource endowment (TRE); tourism ecology promotion (TEP)).

4.6 Analysis of high-level of tourism eco-transformation

1) Technology-pulling organization: H1 (DIL*TIC*TEC*~TRE*~TEP), indicating low tourism resource endowment and government ecological promotion, but favorable technology conditions have enabled tourism places to connect with other provinces for eco-transformation.

The lack of tourism resources is not conducive to informing tourists (Gnoth, 1997; Gössling, 2017). However, technological innovation provides a knowledge store for tourism governments, and the high digital information level reduces the difficulty for tourists to access information. In addition, it facilitates the decision-making, coordination, and control systems utilized by tourism destination governments (Buhalis and Law, 2008). As a result, tourist destination governments establish tourism alliance strategies with foreign provinces (Brandão et al., 2019). In alliances, members can easily access each other's natural and material resources (Pham et al., 2021). According to social capital theory, effective external connectivity is also a resource (Poder, 2011; Pham et al., 2021). It can compensate for the lack of tourism resources and make a destination more resilient (Pham et al., 2021). We find that technological conditions have a profound impact on TET, and studies have also shown that digital technologies, such as the level of digital finance and blockchain technology, can optimize the allocation of tourism resources and thus improve allocation efficiency (Erol et al., 2022; Wang et al., 2022).

This configurational type covers 12.1% of the cases, represented by Tianjin and Sichuan provinces. For example, the Tianjin Municipal Bureau of Culture and Tourism has joined forces with Unicom to deepen the development of "Internet + Tourism," enhancing the tourism industry's digital information and strengthening tourism technology innovation. Also, the Tianjin Cultural Tourism Bureau has actively promoted cultural tourism investment. It includes strengthening project docking and establishing cultural tourism projects with many provinces.

Proposition 1: Tourism's technical conditions can effectively attract the government's external connections and compensate for losses in resource endowment and ecology promotion.

2) Organizational proactive drive: H2 (~ER*~TIC*TEC*TRE*TEP), indicating that macro-environmental regulation is weak and technology innovation capability is limited. However, the government of the tourism area promotes ecology, exploits tourism resources, and establishes strategic links with nearby provinces, promoting eco-transformation.

Unlike the configurational condition H1, H2 is more dependent on organizational effort. Based on Dynamic Capabilities Theory (Eisenhardt and Martin, 2000), the government's initiatives to integrate, construct, and allocate internal and external resources will likely lead to improved environmental performance and eco-transformation of tourism sites. It remains consistent with the current literature (Domingues et al., 2015; Camilleri, 2016). Several studies have shown that tourism organization efforts significantly impact performance (Reid et al., 2008; Domingues et al., 2015; Camilleri, 2016; Prima Lita et al., 2020), and our results reinforce the importance of local governments in promoting TET.

The configurational type covers 15.3% of the cases, representing Fujian Province and Yunnan Province. For example, deep in China's interior, Yunnan Province has less developed technical conditions. The provincial government advocates for the development of green and low-carbon tourism models in the "14th Five-Year" Tourism Development Implementation Plan, demonstrate green development for tourism enterprises such as attractions and B&B inns and educates tourists about eco-tourism. Tourism authorities rely on Bai culture to develop national and provincial tourism resorts. It has led to strategic alliances with neighboring provinces to share tourism resource elements and contribute to the Great Shangri-La Tourism Loop.

Proposition 2: When the regional technical conditions are backward, the government should take the initiative to use tourism resources fully, promote the concept of eco-tourism and pay attention to external connections.

3) Environmental stress organization: H3 (~DIL*~TIC*ER*TEC*~TRE*TEP), indicating the province is technologically backward and tourism resources are limited. However, the high intensity of environmental regulation pressure forces the tourism place government to respond, such as strengthening ecology promotion and increasing tourism foreign economic interaction.

Contrary to H1 and H2, H3 emphasizes environmental regulation. Environmental regulation can positively influence tourism enterprises and scenic spots to practice pro-environmental behavior, reduce tourism carbon emissions, and improve environmental performance (Peng et al., 2017; Chen et al., 2021). Macro-environmental regulation may drive the implementation of ecology promotion and external connections by tourism authorities. Both ecology promotion and external connections can positively influence TET, in line with existing research findings. It is also consistent with the contingency theory that the environment may influence tourism organizational behavior (Rodríguez-Díaz and Pulido-Fernández, 2020).

The configurational type covered 11.5% of the cases. The representative case is Guangxi. To compensate for poor technical conditions, Guangxi emphasizes two-way interactions between "organization and environment," increasing investment in environmental protection on the one hand. From 2013–2019, Guangxi invested 100 billion yuan in promoting the development of the ecological economy and green industry; on the other hand, the provincial government paid attention to the construction of major tourism projects and critical projects for investment.

Proposition 3: When faced with inadequate technical factors and tourism resource endowments, the government ought to pay attention to environmental regulation, promote eco-tourism, and take initiatives in guiding tourism projects.

4) Comprehensive drive type: H4 (DIL*TIC*ER*TRE*TEP); H5 (DIL*TIC*ER* TEC*TEP); H6 (TIC*ER*TEC*TRE). H4, H5, and H6 all involve organizational, technological and environmental factors in the TOE framework, and are therefore named comprehensive drive type. It constitutes the mainstream path for high-level of TET.

H4, H5, and H6 embody the phenomenon of "independently reaching the same conclusion." Tourism resource endowment, external connections, and digital information level all exist in different configurations, but they all promote high-level of TET. Our findings demonstrate the equivalence principle proposed by Woodside. The equality principle states that a sufficient model is not necessary for an outcome to achieve a high score (Woodside, 2014). Technology innovation capability and environmental regulation are effective drivers of TET, in line with the literature. The remaining conditions are volatile and require consideration of the overall nature of the portfolio. It is also consistent with the complexity of TET (Goeldner and Ritchie, 2007; Schianetz et al., 2007).

The coverage of these three configurational conditions is greater than 30%, and the representative cases are Zhejiang, Beijing, etc. Take Zhejiang Province as an example. Zhejiang Province relies on technology innovation capability and attaches importance to digital technology scene application. As a result, digital technology ecology will help turn tourism resources into flows through leveraging technological development.

Proposition 4: Emphasizing the configurational effects of organizational, technological, and environmental factors is more conducive to flat TET.

4.7 Analysis of not-high-level of tourism eco-transformation

1) Comprehensive absence: L1 (~DIL*~ER*~TEC*~TRE*~TEP), L2 (~dil*~tic*~er*~tec*~tep), L1 indicates that technology innovation capability is backward, environmental regulation pressure is weak, and tourism resource endowment is insufficient. L2 indicates low digital information levels, low pressure of environmental regulation, and low level of organizational effort. All the above are not conducive to eco-transformation.

The TOE framework's lack of environmental, technical, and organizational elements was not conducive to developing TET. Essentially, it reaffirms Resource Dependence Theory's argument that TET requires key conditions (Hillman et al., 2009). The absence of digital information level, environmental regulation, tourism external connections, and tourism ecology promotion may lead to not-high-level of TET. At not-high-level, we also find the phenomenon of the equivalence principle between configurational paths (Woodside, 2014).

L1 and L2 cover 27.7% and 24.9% of cases, respectively; the typical cases in L1 are Ningxia and Heilongjiang provinces; the typical cases in L2 are mainly in Ningxia and Xinjiang. Most of these cases are located in western and northeastern China, and the conditions to promote TET are seriously lacking. According to Hillman, Withers, & Collins (2009), there should be certain essential critical conditions for TET.

Proposition 5: The absence of organizational, technical, and environmental factors may be detrimental to eco-transformation

2) Respectable: L3 (tic*~er*~tec*~tre*~tep), which indicates that although the technological innovation capability is strong, the government of the tourism area has made low efforts and has not applied it to the field of tourism scenarios, which is not conducive to transformation.

Although technology innovation capability may increase tourism productivity (Nguyen et al., 2021), we find that high-level of technology innovation capability do not effectively drive TET. Even so, this echoes the view that tourism phenomena are complex and need to be contextualized. Tourism authorities can take the initiative to combine technological innovation capabilities with real-life scenarios (Mendoza-Moheno et al., 2021).

This configuration covers 25.2% of the cases, and the representative cases are Qinghai and Hainan. Hainan Province, located in the east of China, has shown a high capacity for technological innovation due to spillover effects from Guangdong Province. However, tourism activities in Hainan Province are still based only on natural resources and do not combine tourism scenarios with technological innovation.

Proposition 6: Regional science and technology innovation is capable, but inappropriate government application to the tourism scene is equally detrimental to transformation.

4.8 Horizontal analysis of antecedent conditions

We conducted a horizontal analysis to examine the degree of importance of antecedent conditions. A comprehensive comparison of condition combinations showed that environmental regulation was prominent in the configuration of high-level transformation (e.g., H3, H4, H5, and H6). In contrast, the not-high-level transformation configuration has low environmental regulation strength (e.g., L1, L2, and L3), indicating that environmental regulation is vital for transformation. It is in line with Chen and Erdoğan's view that environmental regulation can exert external pressure on tourism sites, thereby curbing carbon emissions and driving TET (Chen et al., 2021; Erdoğan et al., 2022). Correspondingly, tourism external connections appear in H1, H2, H3, H5, and H6. The paths of not-high-level transformation all have low external connections strength. It is in line with Pham and Kofler's view (Kofler et al., 2018; Pham et al., 2021). Tourism ecology promotion is similar to the above. Our findings reaffirm Nistoreanu and Cai's view that ecology promotion increases resident and tourist loyalty, which drives TET (Nistoreanu et al., 2020; Cai et al., 2021). However, in contrast to existing research, we found that the province can achieve high-level transformation regardless of digital information level, technological innovation capability, and tourism resource endowment. This result is consistent with Fiss's assumptions about the configuration approach: "conditions that produce high-level are not necessarily the antithesis of conditions that produce not-high-level" (Fiss, 2011). Therefore, Tourism authorities should effectively combine digital information level, technology innovation capability, and tourism resource endowment with other conditions.

4.9 Robustness checks

There are four common ways to test robustness: increasing the case consistency cutoff, improving the PRI consistency, adding or removing cases, and adding other conditions (Chen and Tian, 2022). For robustness testing, We can select one of the four robustness tests. In this paper, we raise the case consistency cutoff from 0.800 to 0.815 while all configurational conditions remain unchanged. In the not-high-level transformation, the configurational conditions did not change. As a result, the research results remained robust.

5 Conclusion

Based on the TOE configuration framework, we examined 30 Chinese provinces' TET paths from 2016–2019 using fsQCA.

Firstly, China's TET has been increasing from 2016 to 2019. Mainly, it shows a "U"-shaped pattern of falling and rising. Spatial patterns are stable, with hot spot areas and sub-cold spot areas concentrated east of Hu Line and cold spot areas concentrated west of Hu Line. Secondly, we found that the presence of a single condition is not sufficient to predict the effect of TET. From a configurational perspective, high-level and not-high-level TET can be achieved in various ways. In conjunction with the TOE framework, we have identified four high-level paths, namely the "technology-pulling organization," the "organizational proactive drive," the "environmental stress organization," and the "comprehensive drive." Two not-high-level paths were also identified: "comprehensive absence" and "respectable."Third, tourism external connections, environmental regulation, and tourism ecology promotion are the key conditions to promote TET, but digital information level, technology innovation capability, and tourism resource endowment depend on the situation.

6 Discussion

6.1 Theoretical implications

Firstly, we propose a conceptual framework for analyzing TET, referred to the TOE framework. It is based on a summary of existing research results, including environmental (Fernández-Robin et al., 2019), organizational (Crouch, 2011; Brandão et al., 2019; Losada and Mota, 2019), and technological factors (Losada and Mota, 2019; Shu et al., 2022). Scholars can utilize this framework to analyze TET generally and expand the application of TOE theory.

We can use the TOE framework to explain the phenomenon of "divergent findings." Various studies may report contradictory findings regarding the same influencing factor. For example, scholars suggest enhancing technological innovation capability can drive TET (Erol et al., 2022; Sarpong et al., 2022). We found, however, that the condition produced mutually exclusive results across tourism locations. Our study added context to explain scenarios in which the same variable leads to different conclusions, gaining valuable theoretical insight. It echoes Goeldner's call for "complex tourism scenarios to lead to non-linear relationships between variables" (Goeldner and Ritchie, 2007).

Secondly, we examine TET's conditional variables from a configurational perspective. In other words, we're looking at how different influences can affect TET together. Previous studies have demonstrated from a single dimension that TET may be related to the organization, technology, and environment, respectively (Goeldner and Ritchie, 2007; Reid et al., 2008; Peng et al., 2017; Kornilaki et al., 2019; Tkaczynski et al., 2020; Sarpong et al., 2022). However, these three factors are limited in how they are interconnected. Our work fills this gap.

Additionally, existing TET studies tend to assume that causality is symmetrical (Peng et al., 2017; Ji and Wang, 2022). However, Fiss (2011) argues that conditions (or combinations of conditions) that explain an outcome may differ from those that don't. We argue that the "dilemma" and the "way out" of TET are not always symmetrical. Avoiding negative and promoting positive outcomes in management research is equally important. Our work discusses the configurational paths that produce high and not-high-level of TET.

Finally, we propose an alternative method of analyzing the determinants of tourism performance called "Super-EBM + fsQCA." We can then conduct a fine-grained exploration of causal relationships between conditional variables and tourism performance. In the management field, the two-stage analysis of DEA + fsQCA has been gradually used (Amara et al., 2020; Prokop et al., 2021). To our knowledge, scholars have yet to use fsQCA to examine tourism performance determinants.

6.2 Managerial implications

The local tourism administration should formulate TET strategies in a system-coordinating manner. The local government can holistically integrate all the elements of TOE theory to enhance synergistic integration between them. A critical factor in H1 is digital information level and technology innovation capability (Peng et al., 2017; Loureiro, 2019; Shu et al., 2022), but local governments will also need to reach a consensus with neighboring provinces on tourism alliances to compensate for the lack of resources and other factors. On the other hand, in H3, tourism sites have poor technical conditions, but environmental regulations are essential in connecting them to the outside world and launching ecological campaigns (Chen et al., 2021). As a result, when local governments implement TET policies, they can take a holistic approach coupled with the development model and specific configuration combinations.

Secondly, we propose four configurations with high TET and two configurations with not-high TET, which can provide tourism place governments with options in responding to environmental changes. However, managers need to choose the appropriate development model according to the characteristics of the tourism area. Specifically, the promotion of TET differs between eastern, central, and western China. Tourism authorities should determine the development paths for different regions based on their organizational, environmental, and technical conditions. For instance, those cities in the middle and west need to deal with low technology and a lack of innovative resources. They need to give full play to the government's initiative, boost publicity and improve strategic cooperation among provinces to promote TET, whereas, in the eastern regions, they can make use of factor allocation. It echoes the view of scholars who oppose the "one-size-fits-all" approach to managing tourism sites (Goeldner and Ritchie, 2007).

Finally, although these conditions are not necessary for TET, tourism ecology promotion, external connections, and environmental regulation are essential factors that contribute to its promotion (Minoli et al., 2015; Brandão et al., 2019; Chen et al., 2021). Regional governments can enhance communication and technology flow among provinces and cities by forming regional tourism alliances and circuits. We should also intensify the promotion of sustainable tourism and eco-tourism. New tourism scenarios, such as digital scenarios, can be used to promote eco-tourism knowledge. Considering digital information level, technology innovation capability, and tourism resource endowment, combining the remaining conditions and focusing on application scenarios is necessary.

6.3 Limitations and future research

Despite some limitations, the research provides opportunities for further research. Firstly, we discuss TET among provinces based on a Chinese scenario, which may provide a valuable reference for managing tourist sites in developing countries. However, individual administrative units in developed countries continue to face the issue of TET. We still need to examine our findings based on the contexts of different countries and broaden the research context to improve their generalizability. Secondly, we have studied the configurational effects of organization, environment, and technology on TET, which pertain to the macro scale. However, we have not yet examined individual-level factors such as green aspirations and tourism preferences among tourism site residents. By combining the questionnaire data, scholars can compensate for the lack of microscopic scale. Then, scholars can broaden the scope of their research topics by exploring urban clusters, economic zones, or country-based alliances. Finally, as far as research methodology is concerned, we examine the static configurational effects of TET from a cross-section. Future studies may incorporate time-varying factors to explore the dynamics of TET. Thus, we use fsQCA to detect synergistic effects between TOE factors and TET, but the results do not indicate how strong the effects are. Other methods in future studies could measure it.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

CW contributed to conception and design of the study. CW and YZW organized the database. CW performed the statistical analysis. CW wrote the first draft of the manuscript. CW, CWW, HMZ, and QJZ wrote sections of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

Funding

The Projects Supported By Introduction of Talents of Minjiang University Science and Technology Pre-research Project "Research on the impact of Green Advertising Appeals on consumers' Willingness to Pay Premium for Green Agricultural Products" and Supported By Provincial Natural Science Foundation "The Evolution of Tourism Eco-efficiency and High Quality Development Path in Fujian Province under the "Dual Carbon" Goals" (2022J01150).

Acknowledgments

We would like to thank the Ministry of Natural Resources of the Chinese Government for providing open-source maps with review number GS (2019)1697 (http://bzdt.ch.mnr.gov.cn), and the base map has not been modified. We would also like to thank Lele Xu and Decong Tang for data collection.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.1012856/full#supplementary-material

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TYPE Original Research
PUBLISHED 29 September 2022
DOI 10.3389/fenvs.2022.1022929

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The impact of environmental regulation on water resources utilization efficiency

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SPECIALTY SECTION
This article was submitted to Environmental Economics and Management, a section of the journal Frontiers in Environmental Science

RECEIVED 19 August 2022
ACCEPTED 14 September 2022
PUBLISHED 29 September 2022

CITATION
Wang Q and Wang S (2022), The impact of environmental regulation on water resources utilization efficiency.
Front. Environ. Sci. 10:1022929.
doi: 10.3389/fenvs.2022.1022929

With the rapid development of economy and the increase of population, water consumption has increased in China. Meanwhile, water waste, water pollution and uneven distributions of water resources have posed a great challenge to China's economic development. Hence, the improvement of water resources utilization efficiency has become an important measure to solve the shortage of water resources. In this study, the super efficiency Data envelopment analysis model and Tobit model are adopted to study the impact of environmental regulation on water resources utilization efficiency. The results show that water resources efficiency score is different in different regions in China, where the efficiency score in the eastern region is the highest, followed by the western region and the central region. Environmental regulation negatively affects water resources utilization efficiency and these effects are different effects in different regions. Environmental regulation affects three variables, foreign direct investment, technological innovation, industrial structure, and then affects water resources utilization efficiency through these variables. Based on the above research, we put forward some policy recommendations for increasing environmental regulation intensity to improve water resources utilization efficiency.

KEYWORDS

environmental regulation, water resources utilization efficiency, FDI, technological innovation, industrial structure

1 Introduction

Water resource is a kind of precious natural resource with both economic and ecological values. With the acceleration of urbanization and industrialization in China, the demand for water has been increasing year after year. The unbalanced regional distribution of water resources, serious water waste and pollution, and low utilization efficiency have made the shortage of water resources increasingly serious, which has gradually affected China's ecological environment and economic development. To solve the problem of water shortage in China, we need to increase the water resources or improve water resources utilization efficiency (WRUE). Since water supply is restricted by the stock of water resources, improving WRUE, especially from the perspective of environment, has become a sustainable and important method.

The improvement of WRUE is very important. First, the type of industrial growth of China is resource-driven, therefore, improving WRUE remains necessary for China's green development (Wang et al., 2021). The improvement of WRUE not only alleviates the rising trend of water resource demand, but also guarantees water resource supply. This is advantageous to solve the problem of water shortage. Second, the improvement of WRUE is good to develop a circular economy. The circular economy is a new economic model, which can resolve the problem of resource use and environmental protection, and at last decouple economic growth from environmental destruction (Wang et al., 2021). In recent years, China has experienced a rapid economic development. However, the economic expansion has seriously damaged natural resources and the environment, which has a negative impact on the sustainable development. In order to realize the sustainable development, developing a circular economy through the improvement of WRUE is necessary at the present stage of China.

The effective way to improve WRUE from the perspective of environment is environmental regulation (ER). ER is a restrictive measure, policy, regulation and implementation process for economic activities in order to improve ecological and economic efficiency. It can be classified into three types: command-and-control regulation, market-based regulation and voluntary regulation. Command-and-control regulation constrains the environmental behavior of enterprises through setting a technology standard, establishes the emission standards of air pollutants and punishes the enterprise which violates environment protection laws and regulations. Market-based ER establishes a system of emission charge, emission tax and emission trading. It controls the innovative cost and stimulates innovation vitality by levying punishment tax on enterprises with high pollutant discharge and subsidizing enterprises with low pollutant discharge. The pollution discharge fee and tradable emission allowances can promote the internalization of external costs, reduce enterprise costs and realize environmental and economic benefits, leading to the improvement of WRUE. Voluntary ER is that the pollution discharge of enterprises is under the supervision of the masses. For example, people will report to the government when they find out serious events of the environmental pollution. They will negotiate with polluting enterprises in terms of environmental pollution and economic compensation through the environmental protection organization, and expose various pollution events through network. Enterprises will be under pressure to take measures such as technological innovation and improving efficiency to reduce environmental pollution, which will affect WRUE.

Due to the existence of heterogeneity, the intensity of environmental regulation is different in different regions (Wang et al., 2021). The benefits of developing technological innovation to improve WRUE are lower than the ER cost paid by enterprises under low intensity of ER. Enterprises are intended to pay the cost of environmental supervision and do not conduct technological innovation, which is not conducive to the improvement of water resource utilization efficiency. Under the high intensity of ER, ER brings innovation compensation effects, and the innovation compensation benefit is greater than the cost of ER (Zhang et al., 2021). Enterprises will carry out technological innovation and improve water resource utilization efficiency. Therefore, the impact of ER on WRUE is unstable, which is affected by the intensity of ER.

In this study, the super efficiency DEA model is adopted to calculate water resource utilization efficiency values of 30 provinces and cities in China. The DEA method is a powerful analysis tool, which is proved as an effective method to evaluate the relative efficiency of decision-making units (Song et al., 2018; Wang and Sun, 2018). The Tobit model is adopted to analyze the impact of ER on China's WRUE, and the differences among the eastern, central and western regions are compared.

2 Literature review

WRUE is an important comprehensive index reflecting the effective development, utilization and management of water resources. From the supply side, it refers to the supply efficiency of water resources in the process of aquatic products from production to terminal consumption. From the demand side, it refers to utilization efficiency of water resources in relevant social economic activities. At present, academic circles generally study regional water resources efficiency from the demand side (Dadabaev, 2016; Selvakumar et al., 2017; Lu, 2019).

2.1 Measurement of WRUE

Under the background of insufficient water resources and increasing environmental constraints, more and more scholars pay attention to the measurement of WRUE. At present, there are three ways to measure WRUE: single factor WRUE, total factor WRUE and multi-index comprehensive WRUE.

Single factor WRUE, reflecting water consumption through the input-output ratio, is measured by the intensity of water consumption. For example, water consumption per GDP (Yang and Liu, 2014), net income per unit of water consumption (Cai et al., 2003), productivity per unit of water consumption (Evans and Sadler, 2008), water consumption per mu for agricultural irrigation (Wallace, 2000; Deng et al., 2006; Singh, 2007; Fang et al., 2010). The measurement of single factor productivity is relatively simple and highly operational. However, it is not enough to describe the result of the joint action of various input factors, which cannot reflect the actual production process and the substitution relationship between various input factors. The total factor WRUE includes a variety of factors such as labor and capital, which puts the input-output factors into a unified analysis framework and is more in line with the actual production process (Cheng et al., 2016).

Total factor WRUE measures water resources use based on the relationship between total input and total output, incorporating with labor, capital and economy. Data envelopment analysis (DEA) and stochastic Frontier analysis (SFA) are used to measure total factor WRUE. Two methods measure the efficiency by comparing the gap between the actual input/output of each decision-making unit and the ideal input or output. Cao et al. (2018) used the generalized efficiency (GE) indicator, defined as the ratio of total water consumption (TWC) to total water inflow (TWI) entering the agricultural production system within 1 year, to evaluate WRUE. Kaneko et al. (2004) used SFA to measure agricultural WRUE of six regions in China. They found that agricultural WRUE of northwest China was the highest and that of south coast was the lowest.

With the continuous increase of public concern to environmental issues and the promotion of industrial green transformation and upgrading, The connotation of WRUE changes from focusing on economic benefits to take into account both economic and environmental benefits. A comprehensive index, multi-index comprehensive WRUE, is constructed, which evaluates WRUE from a multidimensional perspective. Xu et al. (2019) evaluated the water input and output efficiency with the aggregating comprehensive indicator calculated by appropriate mathematical methods. Huang et al. (2016) constructed an indicator to evaluate the ecosystem water-use efficiency, which was the ratio of carbon assimilation to evapotranspiration. The index considered not only economic attribute of water resources, but also ecological attribute of water resources.

2.2 Environmental regulation

In early studies, ER is a direct government intervention in the utilization of environmental resources, which is mainly through non-market means. In other words, policies and mandatory means are formulated by the government to ensure economic development while taking into account the ecological environment, so as to reduce the external impact of pollutant emission (Pashigian, 1984). With further research, scholars find that public concern on environmental pollution continues to increase, and media organizations and environmental groups also affect pollution emission of enterprises, which makes non-market means evolve into an informal ER. Pargal and Wheeler (1996) first put forward informal ER, who found that communities usually adopted channels such as negotiation or consultation with factories to promote local factories to reduce pollution through informal regulation when the intensity of formal ER was low.

Scholars have carried out a lot of research on both formal and informal ER. For example, Mulatu et al. (2010), Yuan and Xiang (2018) studied the relationship between ER and innovation. Vogel (2000), Bernauer and Caduff, 2004, Hashmi and Alam (2019) studied the relationship between ER and economic development. López-Gamero et al. (2010), Hao et al. (2018), Karplus et al. (2021) studied the effectiveness of ER. Hanna (2010), Chung (2014), Cai et al. (2016) studied the relationship between ER and foreign direct investment (FDI).

The research on the relationship between ER and resource utilization efficiency mainly focus on cost hypothesis and Porter hypothesis. The cost hypothesis thinks that enterprises have to pay pollution charges due to the ER, which increases the production cost of enterprises. When the technology of enterprises remains constant and the market price is fixed, the increase of cost reduces the profits of enterprises, crowds out the R&D investment of enterprises in production technology and leads to the decline of enterprise resource utilization efficiency. Greenstone et al. (2012) studied the impact of air quality regulations on manufacturing plants' total factor productivity (TFP). The results showed that non-attainment designation was related to a roughly 2.6 percent decline in total factor productivity among surviving plants in heavily polluting industries. The regulations governing ozone had great negative impact on productivity, though negative effects were also evident among emitters of particulates and sulfur dioxide.

Porter hypothesis considered that appropriate ER could produce innovation compensation effects, partially or even completely offset environmental protection cost of enterprises, Innovation compensation effects meant that ER stimulated enterprises' R&D investment and promoted technological innovation. Through technological innovation, country would achieve the "win-win" condition of both environmental protection and economic growth and acquire the first-mover advantage, which would promote the improvement of enterprise productivity and profit. Wang and Shen (2016) investigated the nonlinear relationship between ER and environmental productivity based on the assumption of industrial heterogeneity, and evaluated the optimal regulatory environment. Albrizio et al. (2017) constructed a new Porter Model to study the relationship between ER and total factor productivity. They found that the implementation of ER could promote the improvement of industry total factor productivity in high-technology countries.

2.3 Influencing factors of WRUE

A number of studies have been conducted to explore the impact of natural factors on WRUE. Lawson and Blatt (2014) found that the stomata ultimately controlled 95% of all gaseous fluxes between the leaf and the environment. Therefore, the stomata had an important impact on the water loss and WRUE. They also found that the photosynthesis affected WRUE. Peters et al. (2018), Leakey et al. (2019), Bertolino et al. (2019) reached the same conclusion as Lawson and Blatt (2014). Blankenagel et al. (2018) found that WRUE could be increased by restricting transpiration. Wang et al. (2014), Mbava et al. (2020) found that the climate had an important impact on WRUE. Farooq et al. (2019) found that WRUE was affected by many natural factors such as root system, water absorptivity, temperature, precipitation and photosynthetically active radiation. Mbava et al. (2020) used total water to measure water resource endowment and found that total water is negatively related to water use efficiency.

There are some economic and social factors affecting WRUE. Kaneko et al. (2004) firstly adopted stochastic Frontier analysis (SFA) to measure the technical and water efficiency in agricultural production in China from an economic perspective, and then employed the Tobit model to evaluate the determinants of its efficiency. The results showed that net income had a positive impact on water efficiency. Yao et al. (2018) also found that income level of residents was a variable affecting green total factor water efficiency of industry in China. In addition, open level, measured by the total import and export volume is one of influencing factors of green total factor water efficiency.

Song et al. (2018) analyzed the influencing factors of water resources utilization efficiency. They found that water resource endowment, population density and level of economic development were decisive variables of water resources utilization efficiency. The results showed both water resource endowment and level of economic development negatively affected water resources utilization efficiency, whereas population density positively affected water resources utilization efficiency. Deng et al. (2016) found that there were several economic and policy variables affecting water use efficiency. Among these variables, import dependency, export dependency and foreign trade dependence have a positive impact on water use efficiency while the ratio of added value in agricultural sector and sewage per unit of output has a negative impact on water use efficiency. Zhou and Tong (2022) investigated the impact of industrial urbanization, population urbanization, land urbanization, social urbanization, and urban-rural integration on green water-use efficiency. They found that Industrial urbanization and land urbanization positively affected green water-use efficiency, whereas social urbanization and urban-rural integration negatively affected green water-use efficiency. The findings were of great significance in accelerating the development of new type of urbanization and promoting industrial transformation and upgrading.

Few studies have been conducted to study the impact of ER on WRUE. Song et al. (2018) used the directional distance function and Malmquist (ML) index and Tobit model to estimate WRUE and influencing factors under environmental restrictions. The results showed that WRUE was lack and its regional heterogeneity existed, and water conservation awareness negatively affected WRUE. Jin et al. (2019) calculated green total factor efficiency (GTFE) of industrial water resources and its influencing factors. They found that ER had a negative impact on the improvement of China's GTFE of industrial water resources, but ER in the eastern, central, and western regions had positive impacts on the improvement of industrial water resources.

To sum up, scholars have made fruitful research on WRUE, and they provide a theoretical foundation for this study. According to the existing studies, there is still room for improvements. First, limited attention is given to the impact of ER on WRUE. Is there a linear relationship between these two? Second, so far, little study has incorporated ER, FDI, technological innovation, industrial structure and WRUE into one analytical framework. More specifically, the possible mediating role of FDI, technological innovation and industrial structure has been neglected by most prior research. Third, analysis using sub-samples from different regions in China is insufficient, and the relationship between variables needs to be further investigated. Given this, this study examines the impact of ER on WRUE and assesses the mediating role of FDI, technological innovation and industrial structure based on the provincial-level data of China. Moreover, further analyses are conducted by testing the relationship between the key variables based on the sub-sample data from the eastern, central and western regions.

3 Methods and materials

3.1 Theoretical framework

3.1.1 The mechanism of ER affecting WRUE through FDI

ER affects WRUE through foreign direct investment (FDI). There are two views on ER and FDI location selection: pollution heaven effect and pollution halo effect. The former holds that the increase of ER intensity in the home country increases the production cost of polluting enterprises. In order to reduce production cost and maintain profits, polluting enterprises tend to transfer polluting industries to countries with low intensity of ER. The latter states that the home country of multinational corporations has strict environmental standards and requirements. Therefore, multinational corporations have advanced pollution treatment technology to reduce environmental costs. When investing in countries with high intensity of ER, multinational corporations usually continue to use previous pollution treatment technologies for production. This is conductive to improve environment in the host country.

In an open economy, multinational corporations play an important role in economic development. Local governments strive to attract foreign direct investment for economic growth, sometimes neglecting the cost of ecological environment. For the regions with low intensity of ER, lots of pollution-intensive multinational enterprises may agglomerate in these regions. This leads to the waste of resources and serious environmental pollution, and makes it difficult to improve resource utilization efficiency, including WRUE. The entry of multinational corporations is conducive to the economic development of the host country. With the economic development and the improvement of environmental protection requirements, the intensity of ER will increase. When the intensity of ER is high, multinational corporations have to rely on advanced technology and management to obtain competitive advantage. They achieve low consumption, low emission and low pollution in the process of production, which result in resources conservation and the improvement of resource utilization efficiency. On the other hand, multinational corporations have spillover effects on local enterprises. Local enterprises imitate advanced foreign technology and environmental requirements from multinational corporations and then carry on the technological innovation to obtain effective competitiveness, which leads to improve resource utilization efficiency. The advanced technology and management from both foreign corporations and domestic corporations leads to the overall improvement of water resource utilization efficiency of host country.

With this, we propose Hypothesis 1 and Hypothesis 2:

Hypothesis 1: ER will affect WRUE.

Hypothesis 2: ER will affect WRUE through FDI.

3.1.2 The mechanism of ER affecting WRUE through technological innovation

ER affects WRUE of enterprises through technological innovation. There are Porter hypothesis and cost hypothesis about the influence of ER on technological innovation. Porter hypothesis holds that ER will bring innovation compensation effects. Enterprise will carry out technological innovation, save production resources, improve productivity and reduce pollution under appropriate ER. According to Jaffe and Palmer (1997), Porter hypothesis can be distinguished into three different hypotheses: narrow version of the hypothesis, weak version of the hypothesis and strong version of the hypothesis. The narrow version of the hypothesis focuses on the impact of some ERs on technological innovation. With these flexible regulation policies, enterprises will improve the competitiveness by accelerating technological innovation, offsetting the cost brought by ER and increasing resource utilization efficiency. The weak version of the hypothesis states that ER has a threshold effect on technological innovation. ER has a crowding out effect on enterprises' innovation and increases production cost. When the intensity of ER is over a certain threshold, it will promote environmental R&D investment, and in this process, the utilization efficiency of resource will be affected. The strong version of the hypothesis holds ER is beneficial to technological innovation, because innovation income is larger than ER costs. In other words, ER can make enterprises promote competitiveness, reduce costs and obtain more profits.

The cost hypothesis thinks that ER negatively affects technological innovation and technological diffusion, which is not good to resource utilization efficiency. In order to increase ER intensity, government will levy sewage charges on enterprises and set higher sewage standards. Therefore, the implementation of ER will urge enterprises to invest in environmental pollution treatment in order to meet environmental protection requirement. However, the enterprise resource allocation itself is also fixed. After part of the production investment is used for the construction and implementation of ER, the investment in other aspects will be reduced, including technological innovation investment. Low investment in technological innovation slows down the renewal of technology, backward production technology and aging production equipment, resulting in a large waste of resources. So the cost effect of the ER negatively affects technological innovation and resource utilization efficiency.

Based on the above, we propose Hypothesis 3:

Hypothesis 3: ER will affect WRUE through technological innovation.

3.1.3 The mechanism of ER affecting WRUE through industrial structure

ER affects WRUE through industrial structure. ER is disadvantage to industrial structure and resource utilization efficiency as its intensity is low. According to neoclassical theory, enterprises' production has a follow-up cost effect. Enterprises will increase production costs and reduce profits as the intensity of ER is not high. In order to make up for losses, enterprises will increase the market price of products, which leads to the loss of comparative advantage and crowding out effect on the investment in production equipment and pollution control equipment. Hence, the budget expenditure for industrial development will be reduced, which is not conductive to the industrial transformation and upgrading. On the other hand, enterprises have to make choices between pollution intensive industries with low costs and low polluted industries with high costs due to the ER. To maximize the profit, production factors will be transferred from the clean industrial sector to the high pollution industrial sector, and then the production will be locked in the pollution-intensive industries. This is bad to industrial structure and resource utilization efficiency.

When the intensity of ER increases, the cost of environmental governance is far lower than the sewage cost. Enterprises will introduce more advanced production equipment and pollution control equipment, accelerate the innovation of green technology and eliminate backward production equipment. Through correlative effects and demonstration effects, the industry will change the previous production mode of high consumption and high pollution into the production mode of low-carbon and environmental protection, which is conducive to the upgrading of industrial structure and the improvement of resource utilization efficiency. According to pollution heaven hypothesis, enterprises will actively be far away from regions with high intensity of ER and transfer their industries to regions with low intensity of ER. Different regions adopt different ER measures, resulting in high pollution enterprises in areas with strict ER tend to migrate to areas with low intensity of ER, which will affect industrial structure of moving-out and moving-in areas. At last, the industry in the moving-out areas will realize transformation and upgrading, and the moving-in areas will finally realize the transforming of industrial structure and the increase of resources utilization efficiency with the enhancement of ER.

Based on the above, we propose Hypothesis 4.

Hypothesis 4: ER will affect the water resource utilization efficiency through industrial structure.

3.2 Methods

3.2.1 Super-efficiency DEA model

Data envelopment analysis (DEA) is a relatively effective evaluation means using input-output data. It is a common analysis tool to measure performance. Data envelopment analysis has two methods: one is CCR-DEA model, the other is BCC-DEA model. The CCR model assumes that the return to scale is constant and is mainly used to measure technical efficiency. By comparing the relationship between the combination of input and output of each decision-making unit (DMU) and production Frontier boundary, the model obtains the input-output efficiency score. The input-output score range is between (0, 1). If the score is 1, it means that the input has obtained effective output and the efficiency is the maximum. If the score is less than 1, it means that the input has obtained invalid output.

This method can comprehensively evaluate WRUE and the correlation degree of each index. The index has good inclusiveness, does not need to provide mathematical relationship of input and output variables, reduces the influence of subjective factors to a certain extent, and can comprehensively and objectively evaluate WRUE.

The BCC-DEA model is based on CCR model, which assumes that the return to scale is not constant. The model can measure overall technical efficiency, pure technical efficiency and scale efficiency. The overall technical efficiency is decomposed into pure technical efficiency score and scale efficiency score. The scores of three kinds of efficiency are between (0, 1). In the case of invalid output obtained from the input, the model can judge whether the return to scale is increasing or decreasing. If the return to scale is increasing, the scale should be expanded to focus on the role of input. If the return to scale is decreasing, the scale should be reduced to match the current input.

The BCC-DEA model can test whether the efficiency score of the decision-making unit is effective, but it cannot compare and analyze several decision-making units that are effective at the same time. In order to solve this problem, Andersen and Petersen, 1993 proposed super efficiency DEA based on the traditional DEA model, so that the efficiency of relatively effective decision-making units could also be compared.

It is assumed that the multiple-input-multiple-output evaluation system has s decision-making units, and the indicator system is composed of m input indicators and n output indicators.$X_j = (x_{j1}, x_{j2}, ..., x_{jm})^T$is the input vector of the jth decision-making unit DMU, and x_{jm} is the mth input of the jth decision-making unit, $x_{jm} \succ 0, X_j \succ 0$. $Y_j = (y_{j1}, y_{j2}, ..., y_{jn})^T$is the output vector of the jth decision-making unit DMU, and y_{jn} is the nth output of the jth decision-making unit, $y_{jn} \succ 0, Y_j \succ 0$. The super-efficiency model is as follows:

$$\min \theta - \varepsilon\left(\sum_{i=1}^{m} s_i^- + \sum_{r=1}^{s} s_r^+\right)$$

$$s.t.\begin{cases} \sum\limits_{\substack{j=1 \\ j\neq k}}^{s} \lambda_j x_{ij} + s_i^- = \theta x_{ik_0}, i = 1, 2, 3, ..., m \\ \sum\limits_{\substack{j=1 \\ j\neq k}}^{s} \lambda_j y_{rj} - s_r^+ = y_{rk}, r = 1, 2, 3, ..., n \\ \lambda_j, s_i^-, s_j^+ \geq 0, j = 1, 2, 3, ..., s \end{cases} \tag{1}$$

where θ is the expected value of the goal programming, ε represents the non-Archimedean infinitesimal. λ_j is the decision variable of goal programming, and s^- and s^+ are slack variables.

In this study, we use the super-efficiency DEA model to estimate WRUE. Referring to relevant literature on ER and WRUE (Dadabaev, 2016; Han et al., 2020; Singh and Gundimeda, 2021) and considering the availability of data, we select capital (X_1), labor (X_2), water (X_3), GDP (Y_1) and WD (Y_2)capital, labor and water are input variables, and GDP and WD are output variables. The input and output variables are shown in the table below (Table 1).

TABLE 1 Regional water use efficiency evaluation index system.

	Index category	Index form
Input index	Capital (X_1)	Capital stock
	Labor (X_2)	Employees
	Water (X_3)	Water use
Output index	GDP(Y_1)	Regional GDP
	WD (Y_2)	Total waste water discharge

In Table 1, capital is the stock of fixed capital, which is the weighted sum of previous investment flows measured at constant prices. Total current capital is total capital of the previous period minus depreciation plus current capital, which can be expressed as $K_{jt} = K_{jt-1}(1-\delta_{jt}) + I_{jt}$. K_{jt} is the capital stock of province j in period t, K_{jt-1} is the capital stock of province j in period $t-1$, δ_{jt} represents the depreciation rate of province j in year t, and I_{jt} represents the investment in province j in year t by prices of the current year. The base year is 2004. Labor input is the number of employees in each province and water input is water consumption of each province. The GDP is calculated based on the GDP deflator of 2004 and WD is the total amount of discharged waste water.

3.2.2 Tobit model

Although the super efficiency DEA model can calculate overall technical efficiency, it cannot explore the influencing factors and degrees of the DMU. In order to measure the influencing factors and degrees of the DMU, regression analysis method will be used to establish functional relationship between WRUE and influencing factors. The efficiency scores of super efficiency DEA model are censored on the left, that is, there is a threshold value of 0 on the left of the overall technical efficiency and pure technical efficiency, and there is no restriction on the right. When we use the ordinary least square (OLS) method to investigate influencing factors of efficiency scores, the results may be biased. So we use the Tobit model to analyze the panel model.

The Tobit model is estimated by maximum likelihood method, which can be used when independent variables are discrete and dependent variable is constrained. This paper builds a regression model with WRUE as the explained variable and its influencing factors as explanatory variables.

$$\begin{gathered} y' = \beta_0 + \beta_1 x_1 + \beta x_2 + \cdots + \beta_i x_i + \varepsilon_i \\ \begin{cases} y = y'\left(y' \geq 0\right) \\ y = 0\left(y' < 0\right) \end{cases} \end{gathered} \tag{2}$$

where y is the potential explained variable, y' is the explained variable, β_0 is the constant term, β_i is the regression coefficient, x_i is the explanatory variable and ε_i is the error term.

In this study, ER is a series of policies and measures formulated by the government to normalize the enterprise operations in terms of environment, so as to realize the coordinated development of environment and economy. Since investment governance is the main way of ER in China, we use the ratio of environmental governance investment to GDP to measure the intensity of ER (*envir*). Based on previous studies, we add water resource endowment (*endow*), level of economic development (*gdp*), level of urbanization (*urban*), population density (*popul*), degree of openness (*open*) and water resource pollution (*cod*) as control variables to the model. Among them, water resource endowment is measured by per capita water resources and level of economic development is measured by per capita GDP. The level of urbanization is the proportion of urban population in the total population. Population density is the number of people per square kilometer. The degree of openness is the ratio of the total import and export to GDP and water resource pollution is measured by per capita chemical oxygen demand. The descriptive statistics of data are shown in Table 2. Through the VIF test, we find that there is no serious multicollinearity problem.

According to the results of existing literatures, we adopt the Tobit model as follows:

$$\begin{gathered} dea_{it} = \beta_0 + \beta_1 envir_{it} + \beta_2 endow_{it} + \beta_3 gdp_{it} + \beta_4 urban_{it} \\ + \beta_5 popul_{it} + \beta_6 open_{it} + \beta_7 cod_{it} + \varepsilon_{it} \end{gathered} \tag{3}$$

where i represents province, t represents year, $\beta_i\ (i = 0, 1, \cdots, 7)$ is the regression coefficient, ε_{it} is the residual term and *dea* refers to WRUE.

3.2.3 Data source

Learning from previous research literature (Pei et al., 2021), the data cover 30 provinces. Tibet, Hong Kong, Macao and Taiwan are not included due to incomplete data. The sample periods cover the latest years that data is available. Relevant data are obtained from China Statistical Yearbook 2005–2020, China Science and Technology Statistical Yearbook 2005–2020, China Statistical Yearbook on Environment 2005–2020, and China Economic Network Statistical Database 2005–2020.

4 Research findings

4.1 WRUE and ER

The average value of WRUE is shown in Table 3. From Table 2, we find that there is no obvious trend in China's WRUE and there exist heterogeneity in different regions. The score of WRUE in the eastern region is the highest, followed by the western region and the central region. In the eastern region, scores of WRUE of Tianjin, Beijing, Shanghai and Zhejiang are more than 1, and those of other regions are less than 1. Hainan, Jiangsu and Liaoning are in the bottom three. In the central region, Henan has the highest score of WRUE but Anhui has the lowest score. In the western region, Guangxi, Chongqing and Ningxia rank in the top three in WRUE scores, and the bottom three are Gansu, Xinjiang and Yunnan.

The chart of China's ER from 2004 to 2019 is shown in Figure 1. China's average intensity of ER is fluctuated and has an upward trend. The intensity decreased from 1.24 to 1.11% from 2004 to 2006, then began to rise, reached a peak of 1.65% in 2013. During the following years, the intensity first declined and fluctuated a little, and then increased rapidly after 2018. The intensity of ER in the western region was the largest, which had

TABLE 2 Regional WRUE in China, 2004–2019.

	Region	2004	2005	2007	2009	2011	2013	2015	2017	2019	Mean
Eastern	Beijing	0.983	1.023	1.020	1.037	1.057	1.038	1.038	1.038	1.072	1.032
	Tianjin	1.071	1.074	1.054	1.060	1.056	1.065	1.068	1.064	1.020	1.062
	Hebei	0.995	1.003	1.008	0.982	1.012	1.004	1.003	0.990	0.983	0.999
	Liaoning	0.993	0.966	0.969	0.960	0.978	0.967	0.991	1.030	1.035	0.985
	Shanghai	1.005	0.995	1.005	1.019	1.034	1.041	1.047	1.019	1.012	1.020
	Jiangsu	1.008	1.005	0.992	0.991	0.983	0.965	0.969	0.972	0.987	0.985
	Zhejiang	1.012	1.007	1.016	1.030	0.994	0.987	0.978	0.990	0.992	1.000
	Fujian	1.021	1.010	0.997	1.004	1.004	0.984	0.974	0.967	0.993	0.992
	Shandong	0.992	0.985	0.993	1.011	0.996	0.994	1.001	0.981	0.988	0.994
	Guangdong	0.987	1.001	1.021	1.011	1.001	0.998	0.993	0.984	0.987	0.999
	Hainan	0.972	0.997	1.010	0.955	0.972	0.960	0.964	1.001	1.012	0.982
Eastern mean		1.004	1.006	1.008	1.005	1.008	1.000	1.002	1.003	1.007	1.005
Central	Shanxi	0.969	0.980	0.983	0.974	0.981	0.984	0.985	0.984	0.983	0.980
	Jilin	0.972	0.966	0.962	0.966	0.973	0.964	0.965	0.980	0.977	0.969
	Heilongjiang	1.015	1.007	0.982	0.951	0.962	0.961	0.992	0.964	0.958	0.976
	Anhui	0.974	0.968	0.961	0.974	0.985	0.982	0.975	0.977	0.983	0.973
	Jiangxi	0.951	0.955	0.964	0.973	0.983	0.983	0.981	0.968	0.971	0.969
	Henan	0.993	0.981	0.985	0.986	1.000	0.997	0.990	0.961	0.972	0.984
	Hubei	0.977	0.976	0.979	0.974	0.979	0.976	0.973	0.970	0.990	0.975
	Hunan	0.981	0.982	0.984	0.983	0.982	0.982	0.977	0.990	0.984	0.983
Central mean		0.979	0.977	0.975	0.973	0.981	0.978	0.980	0.974	0.977	0.976
Western	Inner Mongolia	0.928	0.964	0.968	0.992	0.998	0.974	0.971	0.985	0.992	0.977
	Guangxi	1.075	1.038	1.052	1.044	1.004	1.000	0.999	0.985	0.967	1.020
	Chongqing	1.064	1.031	1.000	0.984	0.975	0.967	0.956	1.013	1.009	0.999
	Sichuan	0.975	0.966	0.972	0.964	0.985	0.981	0.968	0.978	0.977	0.974
	Guizhou	0.927	0.959	0.956	0.949	0.971	0.972	0.985	0.971	0.978	0.962
	Yunnan	0.962	0.959	0.947	0.938	0.966	0.969	1.005	0.978	0.993	0.965
	Shaanxi	0.950	0.961	0.964	0.983	0.973	0.962	0.973	0.968	0.977	0.967
	Gansu	0.947	0.972	0.971	0.944	0.956	0.947	0.944	0.944	0.949	0.952
	Qinghai	0.914	0.953	0.956	0.962	0.975	0.974	0.987	1.010	1.011	0.972
	Ningxia	0.918	0.987	0.975	0.981	1.007	1.019	0.975	1.012	1.015	0.987
	Xinjiang	0.932	0.956	0.958	0.954	0.963	0.968	0.961	0.944	0.962	0.956
Western mean		0.963	0.977	0.974	0.972	0.979	0.976	0.975	0.981	0.984	0.976
National mean		0.982	0.988	0.987	0.985	0.990	0.985	0.986	0.987	0.991	0.986

TABLE 3 Variables description statistics.

Variable	Obs	Mean	Std.Dev	Min	Max
dea	480	0.9866	0.0281	0.9144	1.0749
envir	480	0.0047	0.0136	0.0001	0.1672
endow	480	0.6899	0.1228	0.4287	0.9691
gdp	480	0.4085	0.2722	0.0421	1.6422
urban	480	0.1233	0.1026	0.0004	0.5479
popul	480	0.5439	0.1400	0.1278	0.9611
open	480	0.0303	0.0351	0.0011	0.1874
cod	480	0.5254	0.3872	0.0393	1.9820

two peaks, 2.04% in 2013 and 2.94% in 2019, and two valley scores, 1.21% in 2005 and 1.66% in 2017. Among them, Ningxia and Qinghai has higher intensity of ER, which are 2.93% and 2.74% respectively, while Sichuan and Yunnan has lower intensity of ER, which are 0.88% and 1.08% respectively. The years with higher intensity of ER in the eastern region were 2012 and 2019. The years with lower intensity were 2015–2017 and the range of intensity was between 1.01% and 1.03%. The intensity of ER in Beijing is the largest, while the intensity of ER in Guangdong is the lowest. The trend of ER intensity in central China was similar to that in China, with the lowest score of 0.89% in 2005 and the highest score of 2.09% in

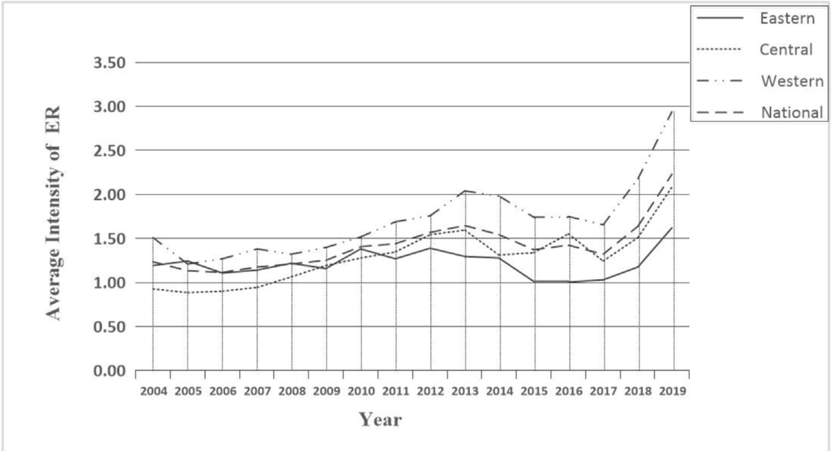

FIGURE 1
Average intensity of ER in China.

TABLE 4 Impact of ER on WRUE.

Variable	(1)	(2)	(3)
envir	-0.215***	-0.204***	-0.210***
	(0.069)	(0.071)	(0.071)
endow	-0.039***	-0.041***	-0.043***
	(0.013)	(0.013)	(0.013)
gdp		0.011*	0.011*
		(0.005)	(0.005)
urban		-0.048***	-0.048***
		(0.017)	(0.017)
popul			-0.013*
			(0.007)
open			0.012
			(0.009)
cod			0.005*
			(0.003)
_cons	1.014***	1.017***	1.025***
	(0.009)	(0.011)	(0.011)
rho	0.587	0.602	0.600
wald	20.28***	28.42***	34.34***

Note: ***, **, and * indicate significant levels at 1%, 5%, and 10%, respectively; the data in parenthesis are standard errors.

2019. Among them, Shanxi has the largest intensity of ER but Hunan has the lowest intensity of ER. Among three regions, the average intensity score is 1.22% in the eastern region, 1.30% in the central region and 1.71% in the western region. This reveals that the intensity of environmental regulation in three regions is low, and these regions should improve the intensity of environmental regulation to better protect the environment. On the other hand, the intensity of environmental regulation in three regions is heterogeneous. Hence, there will be great differences in environmental policies, production and foreign investment in three regions. The intensity of ER in the eastern region was higher than that in the central region before 2011, but lower than that in the central region after 2011. This indicates that the intensity of environmental regulation is not constant, so efforts should be made to improve the intensity of environmental regulation and adjust production and investment accordingly.

4.2 Tobit regression result

4.2.1 Analysis of ER's impact on WRUE

We first study the impact of ER on WRUE and the results are shown in Table 4. ER has a negative impact on WRUE. If the intensity of ER increases by 1%, the scores of WRUE will decrease by 0.21%. This means that the increase of ER intensity is not conducive to the improvement of WRUE. The plausible explanation is that the intensity of ER in China is too low. In this study, we use the ratio of environmental governance investment to GDP to measure the intensity of ER. We find that the national average score of ER is 1.41%, where the highest is 1.71% in the western region but the lowest is 1.22% in the eastern region. According to international experience, the momentum of environmental deterioration can be controlled when the proportion of environmental governance investment in GDP is 1%–1.5%. When the ratio of environmental governance investment to GDP is 2%–3%, the environmental quality can be improved. In some developed countries, the ratio had reached 2% as early as the 1970s. Therefore, the intensity of ER in China is still relatively low. The innovation compensation income is less than the regulation cost when the intensity of ER is low. As a rational economic agent, the enterprise will pay the pollution discharge fee but carry out technological innovation. When the intensity of ER is high, the enterprise will find that the pollution treatment fee to be paid is expensive and innovation compensation income is greater than regulation cost. Hence, the enterprise will get rid of policy constraints by improving technology, which will improve WRUE (Porter and Linde, 1995). Thus, Hypothesis 1 is supported.

There is a negative correlation between water resource endowment and WRUE. The plausible explanation is that areas with abundant water resources have weak awareness of water resource protection and cannot promote enterprises to make water-saving technology innovation, which causes the waste of water resources and low utilization efficiency of water resources. The level of economic development has a positive impact on WRUE. When per capita GDP increases by 1%, WRUE will increase by 0.011%. The possible explanation is that the government has sufficient funds for R&D investment to improve industrial water-saving and emission reduction technologies. On the other hand, the public in developed areas has a strong awareness of environmental protection and high degree of autonomy in water conservation. Therefore, improving the level of regional economic development is a basic guarantee to improve China's WRUE.

The level of urbanization has a negative impact on WRUE. There are three reasons for the result. First, the higher the level of urbanization is, the greater the agglomeration of urban population will be. Most of transferred people enter traditional service industries such as low-end manufacturing and real estate, which has low WRUE. Second, employment, infrastructure and capital pressure in the process of urbanization caused by the transfer of population lead to more extensive investment, and do not pay attention to resource conservation and the improvement of WRUE. Third, the water-saving management system is not perfect in the process of urbanization. For example, low utilization rate of water-saving facilities, low efficiency of rainwater reuse treatment system, and low utilization rate of reclaimed water are not conducive to the improvement of WRUE.

Population density has a negative impact on WRUE, indicating that the increase of population density will increase water consumption and water waste. The increase of population density is related to the acceleration of urbanization, which reflects the concentration of urban population. According to the original data, we find that the population density of 30 provinces in China has increased significantly, and water demand has also increased significantly. The increase of population will increase the demand for urban water, putting severe stress on the ecological environment.

Per capita chemical oxygen demand is the oxidation dose consumed when a certain strong oxidant is used to treat the organic matter in water samples under certain conditions. It can reflect the degree of industrial development and the intensity of pollution control in the region. In this paper, cod has a positive impact on WRUE, indicating that there are deficiencies in the investment and construction of pollution treatment facilities, which cannot improve the sewage treatment rate, reduce the discharge of cod and then reduce the utilization rate of water resources.

4.2.2 Sub-sample test

The intensity of ER in different regions is heterogeneous. In this section, total sample is divided into eastern, central and western sample based on the geographic location of provinces. The results are shown in Table 5. The ER in the eastern and western regions has negative impacts on WRUE, and the absolute value of the coefficient in the eastern region is greater than that in the western region. ER in central region has no significant impact on WRUE. This means that the intensity of ER is too low to exceed the cost threshold and cannot make the innovation compensation income greater than the regulation cost. Enterprises in three regions do not carry out technological innovation to improve WRUE.

The total sample is divided into high-intensity sample and low-intensity sample based on the intensity of ER. The high-intensity sample is the region where the score of ER intensity exceeds the national average, whereas the low-intensity sample is the region where the score of ER intensity is lower than the national average. The last two columns of Table 5 report the results. For high-intensity regions, ER has a negative impact on WRUE. For low-intensity regions, the impact of ER on WRUE is not significant. On the whole, the intensity of ER is relatively low, which cannot promote enterprises to carry out technological innovation, make up for the regulation cost, optimize the industrial structure and improve WRUE.

4.2.3 Mechanism test

ER affects WRUE through foreign direct investment (FDI), technological innovation and industrial structure. In order to further test influential mechanism of ER on WRUE, we carry out mechanism test through two steps. The first step is to test whether ER affects intermediate variables (FDI, technological innovation, industrial structure). The second step is to introduce the interaction term between intermediate variables and ER and test whether the interaction term affects WRUE. The results of the mechanism test are shown in Table 6. ER has a positive impact on FDI. This means that China's FDI has a pollution haven effect in location selection. The high intensity of domestic ER increases FDI enterprises' production costs, especially for pollution-intensive enterprises. Therefore, these enterprises will take advantage of differences in international ER intensity to transfer from home country with high intensity of ER to China, which will cause pollution haven effects (Naughton, 2014). The coefficient of the interaction term between ER and FDI indicates that the inflow of advanced technology and strict standards of multinational corporations is conductive to the improvement of WRUE. Thus, Hypothesis 2 is supported.

ER is not conducive to the development of technological innovation. In order to reach environmental standards,

TABLE 5 Results of the sub-sample test.

Variable	Region			Intensity of ER	
	Eastern	Central	Western	High intensity	Low intensity
envir	-0.228***	0.225	-0.178**	-0.196**	0.505
	(0.076)	(0.709)	(0.087)	(0.083)	(0.381)
endow	-0.063***	-0.039***	-0.033	-0.057***	-0.059***
	(0.019)	(0.012)	(0.021)	(0.019)	(0.016)
gdp	0.014**	-0.002	0.021	0.009	0.008
	(0.007)	(0.008)	(0.013)	(0.013)	(0.006)
urban	-0.053**	-0.011	-0.057	-0.032	-0.058***
	(0.021)	(0.021)	(0.051)	(0.039)	(0.016)
popul	-0.021**	0.008	-0.018	-0.025**	-0.001
	(0.011)	(0.008)	(0.015)	(0.012)	(0.009)
open	0.016	-0.019	0.022	0.016	0.006
	(0.014)	(0.012)	(0.018)	(0.016)	(0.013)
cod	-0.004	0.011***	0.029***	0.015**	0.001
	(0.004)	(0.003)	(0.008)	(0.006)	(0.002)
_cons	1.058***	0.991***	1.003***	1.035***	1.029***
	(0.015)	(0.011)	(0.021)	(0.017)	(0.014)
Rho	0.541	0.017	0.407	0.467	0.734
Wald	36.37***	18.52***	28.68***	29.67***	27.04***

Note: ***, **, and * indicate significant levels at 1%, 5%, and 10%, respectively; the data in parenthesis are standard errors.

enterprises must purchase pollution control equipment or carry out pollution control, resulting in a significant increase in their production costs and a corresponding reduction in investment in R&D (Dean, et al., 2000; Shi and Xu, 2018). The influencing coefficient of the interaction term between ER and technological innovation is lower than that of ER on WRUE in Table 4. This means that technological innovation effect appears less evident when the intensity of ER is low. Hence, Hypothesis 3 is supported. ER has a negative and significant impact on industrial structure. Porter hypothesis holds that high intensity of ER can force enterprises to carry out innovation activities, which will enable enterprises to obtain core competitiveness and have a fundamental impact on industrial structure (Ngai and Pissarides, 2007). However, when the intensity of ER is low, the benefits obtained from technological innovation are lower than the cost caused by a series of ERs such as paying sewage charges. Therefore, enterprises will pay the cost of ER and give up the technological upgrading, which is ultimately not conducive to the upgrading of industrial structure. With this, Hypothesis 4 is supported.

5 Discussion

A large number of studies pay attention the mechanism of ER and FDI. There are two famous hypotheses: pollution heaven hypothesis (Nadeem et al., 2020) and pollution halo hypothesis (Liu et al., 2017). The difference between these two hypotheses is whether the inflow of FDI can increase environmental quality or not under different environmental regulations. Unlike existing study only focusing on the two hypotheses, we further analyze the mechanism of ER affecting WRUE through FDI.

Previous studies mostly focus on the mechanism of ER and technological innovation. Some studies think that ER can increase the internal production costs, weaken the product competitiveness and hinder technological innovation (Gray and Shadbegian 2003). On the contrary, other studies think that proper ER is important for enterprises, because proper ER can stimulate innovation and produce innovation compensate effects, leading to the improvement of enterprises competitiveness (Porter and Linde, 1995). The former and the latter are consistent with the cost hypothesis and Porter hypothesis respectively in our study. Different from existing studies, we further analyze the mechanism of ER affecting WRUE through technological innovation based on the cost hypothesis and Porter hypothesis.

There are few studies on the mechanism ER affecting WRUE through industrial structure. With the acceleration of industrialization and urbanization, city development depends on all kinds of resources. The development and agglomeration of the industry has formed great challenges to ER (Zhou and Tong, 2022). Unlike previous articles focusing on aspects such as resources utilization and industrial structure, ER and

TABLE 6 Results of the mechanism test.

Variable	FDI		Innov		Industry	
	FDI	Dea	Innov	Dea	Industry	Dea
envir	0.004***		-0.006***		-0.009***	
	(0.001)		(0.001)		(0.001)	
envir*FDI		-0.044**				
		(0.021)				
envir*innov				-0.019***		
				(0.006)		
envir*industy						-0.032***
						(0.012)
endow	0.002	-0.044***	-0.002	-0.043***	0.003	-0.043***
	(0.007)	(0.013)	(0.006)	(0.013)	(0.006)	(0.013)
gdp	-0.004	0.011*	0.005	0.010*	0.007*	0.010*
	(0.004)	(0.005)	(0.004)	(0.005)	(0.004)	(0.005)
urban	0.025**	-0.049***	0.031***	-0.048***	0.024***	-0.048***
	(0.010)	(0.017)	(0.009)	(0.017)	(0.009)	(0.017)
popul	-0.010**	-0.013	-0.006	-0.013*	-0.004	-0.013*
	(0.005)	(0.007)	(0.004)	(0.007)	(0.004)	(0.007)
open	0.016***	0.012	0.014**	0.012	0.013**	0.012
	(0.006)	(0.010)	(0.006)	(0.010)	(0.006)	(0.010)
cod	-0.002	0.005*	0.001	0.005*	0.002	0.005*
	(0.002)	(0.003)	(0.001)	(0.003)	(0.002)	(0.003)
_cons	0.038***	1.025***	0.103***	1.026***	0.081***	1.026***
	(0.007)	(0.012)	(0.013)	(0.011)	(0.009)	(0.011)
rho	0.178	0.597	0.152	0.599	0.137	0.598
wald	73.46***	29.67***	111.71***	33.84***	125.52***	32.73***

Note: ***, **, and * indicate significant levels at 1%, 5%, and 10%, respectively; the data in parenthesis are standard errors.

industrial structure, we discuss the mechanism through which ER affects WRUE from the perspective of industrial structure.

In this study, we use the super efficiency DEA method to obtain the scores of WRUE of 30 provinces and cities in China. It can be seen from Table 2 that efficiency scores have the feature of heterogeneity. The eastern region ranks the first and the central region ranks the third. Song et al. (2018) also found the heterogeneous characteristics of WRUE, but the greatest score was in the eastern region, and the score in the central and that in the western region ranked the second and third respectively. For the eastern region, we find that efficiency scores of Tianjin, Beijing and Shanghai are higher than that of other provinces, which is consistent with Song et al. (2018) and Deng et al. (2016). For the central and western region, we find that Anhui and Yunnan have low efficiency scores, which is similar to Deng et al. (2016).

The main reason for these differences is that, first, the method is different. Song et al. (2018) constructed ML productivity index with the DDF and ML index, and ML index included ML technical efficiency (MLTE) and ML technical change (MLTC). They presented environmental technical efficiency scores of 30 provinces and cities in China. Deng et al. (2016) used the slack based measure-data envelopment analysis (SBM-DEA) method to calculate the efficiency score. Second, input and output indicators selected are different. Song et al. (2018) selected social labor force, fixed asset investment and water consumption as input indexes, and selected gross regional domestic product and COD discharge as output indexes. We have the same index category with Deng et al. (2016), but the index form and data processing are different. Hence, we get to different results.

Compared the average efficiency scores in three regions, the trend of three regions are different. For the eastern region, the efficiency score is fluctuated, no evidently ascending or descending trend, and is similar to national average efficiency scores. For the central region, the efficiency score has an unstable fluctuation, fluctuating around a certain score. For the western region, the efficiency score fluctuates and has a general uptrend.

Previous studies have reported that appropriate ER will produce innovation compensation effects, which may offset environmental protection cost of enterprises and achieve the "win-win" goal of economic development and environmental protection (Wang and Shen, 2016; Albrizio et al., 2017). Hence, the proper regulation is of great significance for regional development. In this study, we find that the intensity of environmental regulation is different in different regions due to the existence of heterogeneity (Wang et al., 2021) and the greatest intensity of ER is 1.71% in the western region. According to international experience, the intensity of ER is between 2% and 3%, environmental quality can be improved. It is evident that the intensity of ER is too low to improve environmental quality in China. So these three regions should improve the intensity of ER to better protect environment. This is consistent with the results of the previous study (Zhang et al., 2021). The ER remained important to regional innovation, and both ER and innovation input are main paths for innovation's spillover effect (Wang et al., 2021). This indicates that the Porter hypothesis is valid.

When studying the impact of ER on WRUE, we find that ER negatively affects WRUE. The plausible reason is the rational economic agent will choose to pay the pollution discharge fee but carry out technological innovation because of low intensity of ER. This indicates that there exists a threshold effect of environmental regulation. In the previous studies, the threshold effect of environmental regulation was investigated. Whether environmental regulation was effective on environmental pollution and resource utilization depended on a certain value. When the ER exceeded a certain value, it could significantly reduce environmental pollution and increase resource utilization efficiency. When the ER was below a certain value, it could significantly increase environmental pollution and reduce resource utilization efficiency (Song et al., 2019; Zhao et al., 2021). Similar to previous studies on exploring the relationship between ER and innovation, we find the intensity of environmental regulation is above a threshold value, the innovation compensation income can be more than the regulation cost and the Porter hypothesis is valid.

Comparing with Jin et al. (2019), we get to the same conclusion that ER is not good to the improvement of WRUE. We also have the same explanation for this. One is that the intensity of ER is weak at the initial stage of economy, which leads to a slightly negative effect on the promotion of WRUE. When China enters the rapid development stage, the economic growth is still extensive. Although the intensity of ER has increased, the production cost has increased and enterprises have no sufficient fund in investing R&D, resulting in the crowding-out effect and suppressing effect of ER. During the sub-sample analysis, we find that ER negatively and significantly affects WRUE in the eastern and western region, but positively and insignificantly affects WRUE. Our findings are different from those reported by Jin et al. (2019), they found that the promotion of efficiency in the eastern, central, and western regions was not significant.

Water resource endowment is negatively related to WRUE for the whole country, which is consistent with the previous study (Song et al., 2018). The plausible explanation is that we have weak awareness of water resource protection and cannot promote enterprises to make water-saving technology innovation, leading to the waste of water resources and low utilization efficiency of water resources. During the sub-sample analysis, we find that water resource endowment is negatively related to WRUE for the three regions, but the influencing coefficient is not significant in the western region. According to Song et al. (2018), water resource endowment was negatively related to WRUE in the eastern and western region, but positively related to WRUE in the central region. The reason for this was the differences of industry structure in three regions and weak water resource protection awareness in the whole country.

The degree of openness (*open*) has a positive and significant impact on WRUE, which is similar to Deng et al. (2016). Deng et al. (2016) adopted three indicators of trade as influencing factors to investigate provincial water use efficiency, because they thought that industrial and agricultural production consumed a large amount of water, leading to water trade. And water trade was closely related to water use efficiency. They used import dependence, export dependence and foreign dependence respectively to make empirical analysis, and found that all these indicators positively affected WRUE. Since we focus on the impact of ER on WRUE, the study is not enough in-depth and specific about the relationship between trade indictors and WRUE.

6 Conclusion

In this paper, super efficiency DEA model and Tobit model are used to study the impact of ER on WRUE. According to the result of empirical analysis, we draw the following conclusions.

First, WRUE in China is different in different regions. The score of WRUE in the eastern region is the highest, followed by the western region, and the central region is the lowest. The top five of efficiency scores are Tianjin, Beijing, Shanghai, Guangxi and Zhejiang. The last five of efficiency scores are Gansu, Xinjiang, Guizhou, Yunnan and Shanxi.

Second, ER has a negative impact on WRUE. The plausible explanation is that enterprises choose to pay the cost of ER rather than carry out technological innovation, because the compensation income of technological innovation is less than the cost of ER when ER intensity is low. On the other hand, command-and-control ER makes the government face difficult choices in environmental protection and economic benefits. When economic benefits prevail, it will cause a waste of resources. It is not conducive to the improvement of WRUE.

Third, the sub-sample regression results show that ER in the eastern and western regions is not conducive to the improvement of WRUE, and the impact in the eastern region is greater than that in the western region. ER has no significant impact on WRUE in central China. The results show that ER intensity in these areas is relatively low, which cannot enable enterprises to carry out technological innovation to exceed the cost threshold and then improve WRUE.

Forth, the results of mechanism test show that ER positively affects FDI and affects WRUE through FDI. ER is not conducive to the enterprise's R&D investment. For every 1% increase in the interaction between ER and R&D investment, WRUE will decrease by 0.019%. R&D investment is disadvantageous for the improvement of WRUE. ER has a negative impact on industrial structure, and further negatively affects WRUE through industrial structure.

Given the conclusions, following policy implications are proposed.

First, we should improve the intensity of ER and make it produce incentive effects to the improvement of WRUE. Through this, we can change the original production mode, promote the transformation and upgrading of industrial structure, encourage R&D investment, and finally improve production technology. Command-and-control ER can get obvious implementation effects in a short time. Since it has mandatory and inflexible characteristics and will increase the burden of enterprises over time, the implementation effect is decreased in a long time. Thus, the government should strengthen the publicity and education of environmental knowledge, gradually enhance public awareness of environmental protection, and enhance the enthusiasm of environmental protection organizations. In addition, the government should establish a mechanism system for public participation in environmental supervision, dredge public supervision channels, and improve the intensity of environmental protection.

Second, local governments need to comprehensively consider local conditions and implement differentiated ER due to the heterogeneous effect of ER on WRUE. Command-and-control regulation, market-based regulation and voluntary regulation have their own advantages and disadvantages. Different regions have different responses to various ERs. Local governments should implement ER based on local conditions, gradually abandon extensive economic growth at the expense of the environment, and transit to intensive economic growth relying on technological innovation and industrial structure upgrading, so as to achieve a win-win situation of high WRUE and environmental protection.

Finally, enterprises should increase R&D investment, bring green technology into production process, and promote the rapid upgrading of technology, so as to change the production mode and exceed the cost effect threshold of ER. In the process of opening up to the world, local governments should improve the quality of foreign investment and actively introduce water resource-saving and environment-friendly foreign investment. At the same time, they should strengthen the awareness of water saving in the process of production activities, especially in areas rich in water resources. Local governments should analyze the influencing factors of WRUE such as water resource endowment, level of economic development, level of urbanization and so on. They should strive to create an external environment conducive to the improvement of resources efficiency and promote the improvement of WRUE.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: http://www.stats.gov.cn/tjsj/ndsj/.

Author contributions

WQ: Methodology, Data curation. WS: Investigation, Reviewing and Editing.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 11 October 2022
DOI 10.3389/fenvs.2022.1028508

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OPEN ACCESS

EDITED BY
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SPECIALTY SECTION
This article was submitted to Environmental Economics and Management,
a section of the journal
Frontiers in Environmental Science

RECEIVED 26 August 2022
ACCEPTED 23 September 2022
PUBLISHED 11 October 2022

CITATION
Zhang Y, Cao R, Xiao X, Wei Z, Yang J, Gao Y, Lu S and Zheng C (2022), How to coordinate the use and conservation of natural resources in protected areas: From the perspective of tourists' natural experiences and environmentally responsible behaviours.
Front. Environ. Sci. 10:1028508.
doi: 10.3389/fenvs.2022.1028508

How to coordinate the use and conservation of natural resources in protected areas: From the perspective of tourists' natural experiences and environmentally responsible behaviours

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One of the important purposes of opening protected areas to the public is providing tourists with natural experience products and education so as to stimulate their environmentally responsible behaviours (ERBs) and achieve sustainability. However, there are often contradictions between the recreational use of natural resources and eco-environmental protection, and scholars have not directly determined whether natural experiences always trigger tourist ERBs. To fill this gap, we study the formation of ERBs (including environmentally friendly behaviours, environmental concern-based behaviours and sustainable behaviours) by integrating the mechanisms of tourists' experiences (including sensory experience, mental involvement and norm arousal) and their effects on ERBs. The results of a sample of 682 tourists at a National Nature Reserve in China affirm that there are spillover effects among tourists' experiences and that tourists' experiences influence ERBs. Sensory experience and norm arousal positively affect people's environmentally friendly behaviours, their behaviours that are based on their concern for the environment and their sustainable behaviours. While mental involvement has a positive impact on environmentally friendly behaviours, a negative impact on sustainable behaviours, and no effect on people's environmental concern-based behaviours. In addition, mental involvement and norm arousal play an important role in mediating the impacts of sensory experience on ERBs. This study explores the relationship between use and conservation of natural resources *via* tourists' experiences and ERBs, and it reveals that tourists' experience stays in mental involvement, which may not conducive to eco-environmental conservation in the protected areas. It opens the field for future research paths in the exploration of the paradox that emerges out of the natural experience and tourists' ERBs and provides insights into and points to ecological implications for reserve managers and tourism operators.

KEYWORDS

tourists' experience, resource and environment management, sustainability, spillover effects, environmentally responsible behaviours

1 Introduction

Experience has been emerging as the dominant factor for the success of the tourism industry, along with environmental conservation at tourist destinations, especially in nature-based tourist sites (Wang et al., 2020). However, as tourism grows, adverse impacts on the environment and natural resources may occur due to tourists' inappropriate behaviours (Ballantyne et al., 2011). For example, in 2018, four tourists sneaked into the special protection zone of the picturesque Danxia scenic area in Zhangye City, Gansu Province, China. These tourists directly trampled on the Danxia landscape and lifted the dust, savagely destroying the beautiful landscape that has resulted from the evolution of nature over the last hundreds of millions of years. It is predicted that one of their footprints in the core protected area may take 60 years to disappear on its own. In 2020, an off-road vehicle drifted on the Hulunbuir grassland in China. The body of the vehicle slid rapidly, and black mud splashed under its wheels, illegally crushing and destroying grassland over an area estimated at 1953.3 m^2. Such incidents happen from time to time in developing countries where tourists destroy resources and the environment in order to gain special experiences or where tourists' experiential activities lead to behaviours that damage resources and the environment. These actual phenomena contradict the previous research conclusion that tourists' experiences of nature promote their environmentally responsible attitudes and behaviours (Uriely, 2005; Lee et al., 2015; Kim and Thapa, 2018; Lee et al., 2018; Rosa and Collado, 2019; Radovi, 2021). This paradox raises important study questions: Is the tourists' experience layered? And do all experience dimensions have a positive effect on visitors' behaviours?

Recreation experiences play an important educational role in promoting tourists' environmentally responsible behaviours (ERBs) in the nature-based tourism context (Ballantyne et al., 2011). However, different types of recreational experiences and activities may influence tourists' environmental attitudes and behaviours in various ways (Berns and Simpson, 2009; Lee et al., 2018). Although our predecessors have made great contributions to the research on experience and on the relationship between experience and tourists' behaviours, they have not answered three questions: 1) What is the relationship between the endogenous dimensions of tourists' experiences? That is, are there spillover effects from tourists' experiences? 2) What is the relationship between different dimensions of experiences and behaviours? That is, do all kinds of experiences have a positive effect on ERB? And 3) Do the spillover effects of experiences have an impact on tourists' ERBs? That is, is there a mediating effect of higher hierarchy experiences on the relationship between primary hierarchy experiences and tourists' ERBs? These knowledge gaps have motivated our research, whose conceptual contribution entails the identification and development of theoretical linkages among tourists' experiences, as well as the provision of a deeper understanding of the critical experience antecedents of ERB in nature-based tourist sites. This study also provides practical implications.

Our research seeks to address four objectives. First, we develop and validate a conceptual model to integrate the spillover effects of tourists' experiences and the mechanisms that promote ERBs. Second, we verify that experiences are layered and that higher hierarchy experiences are activated by lower hierarchy experiences. Third, we examine and compare the relative importance of experience variables in affecting ERBs in the nature reserve context. Fourth, we determine the mediation relationships between experience variables (sensory experience, mental involvement and norm arousal) and ERBs.

2 Literature review and theoretical framework

2.1 Nature-based tourism

The main role of nature in attracting tourists to specific destinations is well known (Valentine, 1992). With the rapid development of urbanisation, the demand for nature-based tourism has steadily grown and is the fastest growing sector in the world tourism industry. Laarman and Durst (1987) used the term 'nature travel' to express nature-based tourism, which includes education, recreation and adventure. Boo (1990) used 'eco-tourism' as synonymous with 'nature tourism' and defined it as 'travel to relatively undisturbed or polluted natural areas for the specific purpose of studying, admiring and enjoying the landscape and its wild flora and fauna, as well as any existing cultural manifestations' (Valentine, 1992). Fredman and his colleagues (2010) identified four recurrent themes to define nature-based tourism: 1) visitors coming to a natural place, 2) experiences in an eco-environment, 3) participation in an activity, and 4) normative components related to local impacts (including ecology, the economy, society and local culture). Later, Fredman and Tourism (2010) proposed a minimalistic definition based on the official Swedish definition of tourism that states that nature-based tourism represents human activities occurring when people visit natural areas outside their usual residential areas. Based on a previous understanding of nature tourism, we believe that nature-based tourism is related to recreational activities in natural areas, and the key aspect of nature-based tourism is that tourists are away from home and their experiences take place in nature.

Nature-based tourism has increased worldwide and involves natural spaces such as oceans, wetlands, forests, grasslands, and islands (Ballantyne et al., 2011; Lee et al., 2015; Xu et al., 2018). Protected areas are the focus of many nature-based tourism projects in the world, which has led to an increase in the number of people visiting protected areas. This increase creates a dilemma for protected areas, given their dual mission of protecting wildlife and its habitat and providing visitors with a meaningful experience in the natural environment (Moore et al., 2013). Some scholars have categorised tourists by assessing their recreational experiences, which can be helpful for interpreting tourists' experiences and the implementation of environmentally responsible behaviours in natural areas (Carvache-Franco et al., 2019; Lee et al., 2018). Some researchers have analysed the dimensions and interrelationships of tourists' environmental behaviours to try to essentially address behaviours that interfere with the environment by changing those behaviours (Nilsson et al., 2016; Wang et al., 2020). Additional scholars have studied the mechanisms that are driven by environmentally responsible behaviours from a social psychology perspective, examining motivation, values, experiences, sense of place and so on, to make suggestions and provide guidance for nature-based tourism management agencies to implement scientific and effective environmental protection measures in tourism (Ramkissoon et al., 2013). An increasing number of studies on tourists' experiences and environmental behaviours have shown that tourists' experiential activities have had a profound impact on the resources and environment of tourist destinations; these studies have received great attention from all sectors of society, including academia (Carvache-Franco et al., 2019; Lee et al., 2018).

2.2 Tourists' experiences

In the 1960s, Boorstin first put forward the concept of tourist experience. He considered tourist experience to be a trivial, superficial, frivolous pursuit of vicarious, contrived experiences (Boorstin, 1961). MacCannell (1973) advanced that the fervent pursuit of authenticity and pilgrimages undertaken by modern people were the essence of the tourism experience. For Xie (2010), the tourist experience referred to the experience gained by tourists in the tourism world when they are deeply integrated in their current situations and derive a sense of comfort from their body and mind being integrated. In fact, scholars have shown that tourists may have different motivations for travelling. Different scholars have had different understandings of the concept of experience. However, we accept that the tourist experience is determined by the "centre" to which the visitor adheres, and that this centre represents their personal worldview (Cohen, 1979). In our study, tourist experience is defined as tourists' sensory cognition, psychological feelings and mental thoughts generated as a result of their participation in nature-based tourism activities and based on the specificity of natural resources and the ecological environment of nature reserves.

As modelled by Holbrook and Hirschman (1982), experience includes symbolic, hedonic, and aesthetic dimensions. Pine and Gilmore (1998) suggested that experience entailed entertainment, education, aesthetics, and escape. Schmitt (1999) divided experience into five dimensions: sensory, emotional, cognitive, operational, and related experience. Walls and his colleagues (Wall et al., 2011) proposed four dimensions for experience, which entailed extraordinary, ordinary, emotional and cognitive experience. Ballantyne et al. (2011) proposed that experiential and reflective engagements were part of nature-based tourism destinations. Lee et al.'s (2018) study showed that experiential observation included sensory, learning and experiential reflection and ecological observation. Furthermore, it has been shown that the structure of experience is as diverse as the concept is, and there is a consensus that educational and recreational experiences are increasingly important functions of nature-based environments that contribute to human society and that the constructs of nature-based tourism experiences should include sensory, emotional, functional, and educational elements (Lee et al., 2015).

Existing studies on tourist experience have focused on analysing the dimensions of tourist experience and related knowledge from a speculative angle (Uriely, 2005; Wu and Tang, 2018). Furthermore, factors influencing the tourist experience and the resulting effect of experience value have been discussed from an empirical perspective (Chen et al., 2020; Teng, 2021). Scholars have not paid enough attention to the relationship between the dimensions of experience, and whether there are spillover effects from this experience. The term 'spillover' has been applied to a wide variety of phenomena, including the spread of knowledge, attitudes, feelings, roles, identities, or behaviours attributed to a given domain, group, or location into a different domain, group or location (Galizzi and Lorraine, 2019). In the realm of experience, Hultén (2011) indicated that customers' sensory experiences can intensify brand experiences. In nature-based tourist destinations, tourists' sensory experience constitutes their basic acquisition; mental involvement represents the psychological enjoyment derived from sensory experience (which is the medium hierarchy experience); and norm arousal is the experience of the highest hierarchy order, playing a role in knowledge acquisition, environmental education, norm activation, *etc.* Considering Maslow's hierarchy of needs theory, fulfilling human needs requires a certain sequential relationship; that is, there is a sequential evolutionary path when people demand results, and this demand goes from low to high. Therefore, we formulate the following hypotheses:

Hypothesis 1a: Tourists' sensory experience stimulates their mental involvement.
Hypothesis 1b: Tourists' sensory experience stimulates their norm arousal.
Hypothesis 1c: Tourists' mental involvement stimulates their norm arousal.

2.3 Environmentally responsible behaviours

With the rise of nature-based tourism and the increasing number of tourists, tremendous negative eco-environmental consequences have occurred due to tourists' behaviours. The management and protection of natural resources and the environment have attracted great attention from theoreticians and practitioners (Zhang et al., 2020). It is imperative that we mitigate the environmentally harmful effects induced by tourists' activities and encourage tourists to implement ERBs. ERBs require tourists to have a strong sense of responsibility for local natural and human environmental factors (Wang et al., 2020). For example, tourists may actively participate in eco-environmental protection in destinations, focus on environmental policies and measures in the destination, monitor other tourists or organisations so they comply with aggressive environmental responsibility norms, and even pay attention to local customs and culture related to protecting the environment in the destination (Lee et al., 2015; Wang et al., 2020).

In discussing the driving mechanism of tourists' ERBs, researchers have focused on two aspects. The first one is the establishment of a theoretical framework, and the other is the selection of corresponding influencing factors and analysis of the relationship between those factors on the basis of the analytical framework. Several theoretical frameworks have been widely used to explain ERBs; these are the theory of reasoned action, theory of planned behaviour, value-belief-norm theory, and model expansion (Fishbein and Ajzen, 1977; Ajzen, 1991; Stern et al., 1999; Fu et al., 2019; Shabnam et al., 2021; Wan et al., 2021). It has been shown that environmental values (or attitudes) significantly affect personal ERBs (Kil et al., 2014; Maichum, et al., 2016) and combine environmental knowledge, environmental education, environmental awareness, norms, ethics, satisfaction, motivation, place attachment, and environmental sensitivity as the factors influencing tourists' ERBs (Carvache-Franco et al., 2019; Cheng and Wu, 2015; Farrow et al., 2017; Liu et al., 2020; Varela-Candamio et al., 2018). In addition, some scholars have studied the reasons behind tourists' ERBs from the perspective of destination attractions, destination images, perceived value, recreational involvement and environmental orientation (Wu and Tang, 2018; Kim and Koo, 2020).

Since experience is an important part of tourism activities, it has attracted attention from scholars as a factor influencing tourists' ERBs. Tourists' experiences play an important environmental educational role in promoting tourists' knowledge and ERBs in the nature-based tourism context (Ballantyne et al., 2011; Lee et al., 2015). Millar and Millar, 1996 investigated the impact of direct and indirect experiences on customer attitudes and behaviours. The scholars found that direct experiences were more predictive of customer behaviours than indirect experiences. Although the results of their analysis did not support their proposed model, their findings supported the relationship between recreational experiences and ERBs (Duerden and Witt, 2010). Lee and Jan (2015) found that understanding and appreciating nature through a recreational experience could improve tourists' environmental attitudes and increase their ERBs, and these scholars' empirical model proved that experiences that reflected environmental attitudes impacted tourists' ERBs. Huseynov's (2020) research extended previous research by revealing that not all the dimensions of destination experiences equally influenced tourists' behavioural intentions and that only the sensory and intellectual dimensions of experience could affect behavioural intentions (Huseynov et al., 2020). Xu et al. (2018) provided deeper insight into how each facet of tourist involvement (magnitude and pleasure, risk probability and consequence, and sign value) performed differently in predicting tourist experience and ERBs in Nansha Wetland Park in China. In fact, it has been shown that tourist experience positively and significantly impacts ERBs. Based on these findings, we postulate the following hypotheses:

Hypothesis 2a: Tourists' sensory experience is positively related to their environmentally friendly behaviours (EFB).
Hypothesis 2b: Tourists' sensory experience is positively related to their environmental concern-based behaviours (ECB).

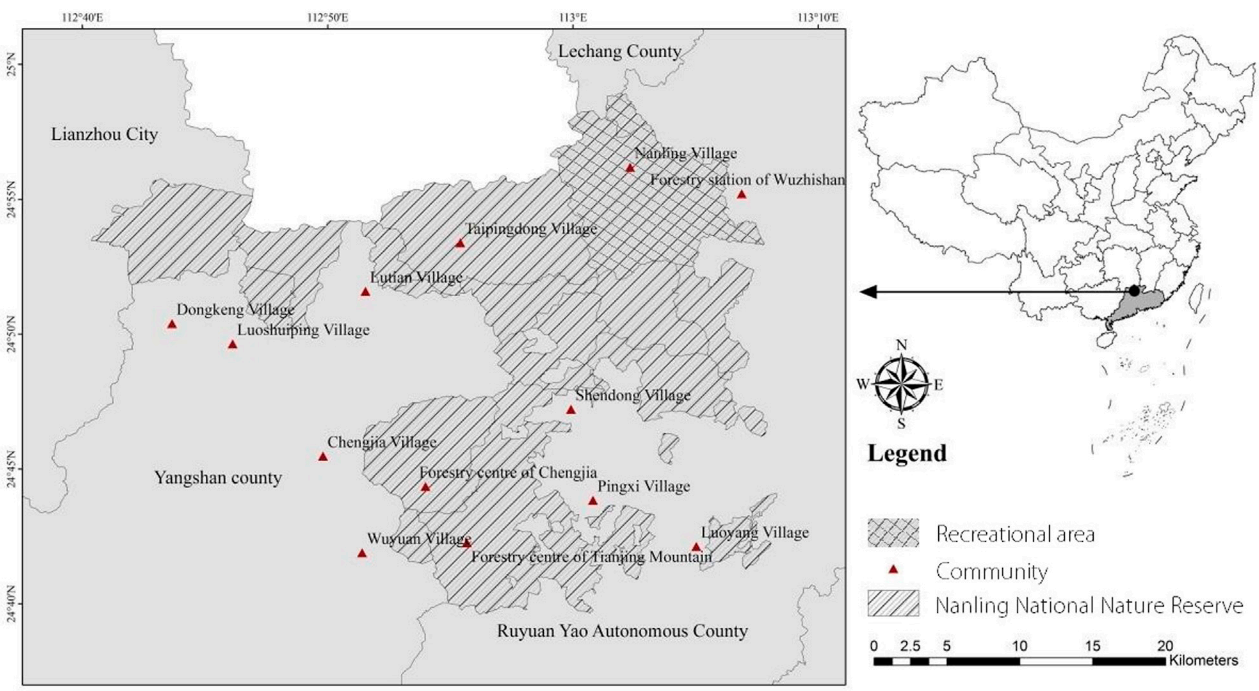

FIGURE 1
Location of nanling national nature reserve.

Hypothesis 2c: Tourists' sensory experience is positively related to their environmentally sustainable behaviours (ESB).

Hypothesis 3a: Tourists' mental involvement is positively related to their EFB.

Hypothesis 3b: Tourists' mental involvement is positively related to their ECB.

Hypothesis 3c: Tourists' mental involvement is positively related to their ESB.

Hypothesis 4a: Tourists' norm arousal is positively related to their EFB.

Hypothesis 4b: Tourists' norm arousal is positively related to their ECB.

Hypothesis 4c: Tourists' norm arousal is positively related to their ESB.

3 Materials and methods

3.1 Study site

Nanling is the largest mountain range in southern China and an important natural geographical boundary located at the border of Guangdong Province, Hunan Province, Jiangxi Province and Guangxi Zhuang Autonomous Region in China. The Guangdong Nanling National Nature Reserve is located in northern Guangdong Province, at the southern foot of the middle section of the Nanling Mountains and within the administrative boundaries of Ruyuan County, Shaoguan City, Yangshan City, Qingyuan City and Lianzhou City, Guangdong Province (Figure 1). The forest coverage rate in the Nanling Nature Reserve is 90.6%, which allows for the preservation of the complete mountain forest ecosystem and vegetation vertical belt spectrum. There are 2,608 species of wild vascular plants in the Nanling Nature Reserve, among which 30 species have been placed under special state protection. There are 486 species of terrestrial vertebrates, accounting for 18.4% of the total number of terrestrial vertebrates in China (2,638 species). Therefore, Nanling has been called a subtropical species genetic bank. Moreover, it is the source of almost all major rivers in Guangdong Province. One hundred million people depend on Nanling for drinking water and crop irrigation, and the region has also been called the Guangdong Water Tower.

The area constitutes an abundant and rare biological resource, and its high-quality ecological environment provides conditions for the development of natural sightseeing in the Guangdong Nanling Nature Reserve. However, due to unreasonable development, ecological damage in the core area of the nature reserve has been a serious issue. The State Environmental Protection Administration of the People's Republic of China ordered business to be suspended in the region in May 2018 so that improvements could be made. To date, Guangdong Nanling Nature Reserve has not been allowed to receive tourists again, and only a few nature education activities have been allowed in the buffer area. Studying the relationship between tourists' experience and ERBs in the Nanling Nature Reserve will usher its reopening, ensure the quality of tourists' experiences and provide scientific guidance for protecting the ecological environment.

3.2 Sampling and surveying

The pilot survey was conducted with 30 tourists who visit Nanling National Nature Reserve. Finally, 26 items were comprised in the formal questionnaire after reliability and validity analysis. The survey was conducted in October 2017 and April 2018 for a total duration of 15 days. The targeted respondents for this study were nature-based tourists who visited the five sightseeing and rest areas inside the reserve. A convenience sampling method was employed to collect data during daylight hours. Eight trained research assistants administered the questionnaire survey. Each respondent was informed of the research purpose and variables and asked if he or she would like to participate in the interview process. Additionally, small gifts were offered to those who agreed to participate in the survey. We distributed 800 questionnaires, and 724 were returned. After discarding 42 questionnaires due to too many missing values and outliers, 682 questionnaires were used for final analysis, yielding a response rate of 81.00%.

3.3 Questionnaires and measurement scales

Together with the classification questions related to the sociodemographic variables, the measurement scales used for constructing tourists' experiences and ERBs, which were addressed in the proposed conceptual model, were included in a structured questionnaire. These constructs were measured as follows:

The section covering tourists' experiences was based on Ballantyne's (2011) findings, Lee's (2015) scales, as well as our own field observations and five visitors' interview results. Interview questions include "What kind of experience did you have when you came here?", "What concern did you have about when visiting here?", and "What have you got here, especially in environmental education?". Eventually, a 14-item scale for tourists' experiences was developed according to the answers of the respondents and relevant literature, and measured by the 5-point Likert-type scale. It comprised sensory experience (seven items), mental involvement (three items), and norm arousal (four items).

ERBs were measured on a twelve-item, 5-point Likert-type scale based on Zhang's (2015) scale, as well as our on-site observations. The ERBs included environmentally friendly behaviours (four items), behaviours linked to concerns about the environment (four items) and sustainable behaviours (four items).

The demographic variables consisted of gender, marital status, age, educational level, occupation, residential region, and monthly income.

3.4 Quality of the research instrument

The survey results were accurate within a 4.62% sampling error with a confidence level of 95% in the Guangdong Nanling National Nature Reserve. Moreover, the sample sizes in the empirical survey appeared to be adequate for performing a structural equation modelling analysis based on the findings by Westland (2010). All factor loadings of the measurement indicators were higher than 0.550 (Table 1). The Cronbach's alpha scores and KMO scores for the total measurement instrument and latent variables of environmental conservation behaviours and experience were 0.867 and 0.910, respectively, and 0.831 and 0.903, respectively. All of the Cronbach's alpha scores exceeded the benchmark of 0.800, and the KMO scores exceeded 0.800, indicating that the research instrument had an acceptable internal consistency for measuring items in the same construct (Vaske, 2008).

3.5 Data analysis

Descriptive statistics as well as exploratory factor analysis were evaluated with SPSS 21.0 for Windows. Amos 21.0 for Windows was used for the confirmatory factor analysis (CFA) and SEM. To ensure the quality of the measurement, model fitting, composite reliability, convergent validity and discriminant validity were tested for the tourist experience and ERB scales. Then, SEM analysis was used to estimate all the parameters with the maximum likelihood method. Third, all hypotheses were tested to determine the direction and significance of the relationships among factors (Hair et al., 2010). Finally, the mediating effects were tested in the conceptual model with the bootstrapping method by Amos 21.0.

4 Results

4.1 Sample profile

The final sample (n = 682) contained a higher proportion of males (55.1%) than females (44.9%). The most frequently reported age groups included people between 20 and 29 years (48.2%) and 30 and 39 years (29.9%), while other groups were represented in smaller proportions. Most respondents had received college and university level education (450) and had

TABLE 1 Construct measurement summary.

Factors	Indicators	Mean	Factor loading	Items-total correlation	CR	AVE
Measurement scale of environmental responsible behaviours (KMO = . 831 a = 0.867)						
EFB	Do not disturb the plants	4.375	0.804	0.534	0.815	0.526
	Do not feed animals	4.455	0.751	0.434		
	Keep clean and tidy	4.229	0.779	0.549		
	Actively avoid scenic spots that need ecological restoration	4.232	0.754	0.523		
SB	Respect local customs	3.780	0.642	0.567	0.817	0.531
	Prevent others from disturbing the environment	3.396	0.851	0.525		
	Actively collect rubbish found on the ground	3.502	0.795	0.541		
	Respect the life of local residents	3.387	0.811	0.615		
ECB	Pay attention to the quality of the environment in the reserve	4.106	0.734	0.557	0.819	0.531
	Worry about environmental damage in the reserve	4.249	0.823	0.566		
	Pay attention to the official attitude in the reserve	3.956	0.681	0.606		
	Worry about the loss of biodiversity in the reserve	4.085	0.780	0.555		
Measurement scale of experience (KMO = 0.902 a = 0.867)						
SE	Numerous animals and plants	4.325	0.571	0.678	0.871	0.500
	Fresh air	4.774	0.830	0.636		
	Good water quality	4.742	0.823	0.688		
	Picturesque scenery	4.748	0.839	0.741		
	Comfortable climate	4.460	0.699	0.575		
	Overall Landscape Coordination	4.461	0.745	0.659		
	Overall environmental comfort	4.478	0.613	0.706		
MI	Feel happy	4.434	0.843	0.646	0.877	0.704
	Feel relaxed	4.475	0.867	0.683		
	Escape everyday stress	4.349	0.828	0.551		
NA	Inspire personal ethics	4.006	0.858	0.715	0.834	0.560
	Raise personal environmental awareness	4.114	0.842	0.692		
	Correct some behaviours	3.777	0.771	0.601		
	Re-examine one's behaviours	3.874	0.792	0.624		

SB, sustainable behaviours; EFB, environmentally friendly behaviours; ECB, environmental concern-based behaviours; SE, sensory experience; MI, cognitive involvement; NA = norm arousal.

TABLE 2 Correlation matrix of the constructs.

Constructs	EFB	SB	ECB	SE	MI	NA
EFB	0.725					
SB	0.420*	0.727				
ECB	0.437*	0.575*	0.727			
SE	0.577*	0.300*	0.477*	0.707		
MI	0.668*	0.250*	0.507*	0.657*	0.839	
NA	0.582*	0.591*	0.604*	0.465*	0.642*	0.748

*$p < 0.05$. The bold numbers on the diagonal are the square roots of average variance extracted.

a personal monthly income below RMB 60,00 (64.7%). Employees of enterprises and public institutions and students and freelancers were the main source markets (24.7%, 23.2%, 13.8%, respectively).

4.2 Measurement model

The measurement model consisted of six constructs and 26 measurement items. Composite reliability was assessed to achieve the complete results of internal consistency, with values higher than 0.800 across all variables (Table 1). The measurement reached convergent validity at the item level because all factor loadings exceeded 0.500. Furthermore, convergent validity was also evaluated by average variance extracted (AVE), with values higher than 0.500 across all variables (Xu et al., 2018), as summarised in Table 1. These values demonstrated the measures' high internal consistency. As shown in Table 2, all correlation coefficients between the factors were significant and under 0.800, showing the distinctiveness of each factor (Xu et al., 2018). All values intercorrelated between subdimensions fell below the suggested threshold of 0.850 (Table 2), providing evidence

TABLE 3 Model fitting index.

Fit index		Criterias	Spillover effects among tourists' experiences model (model 1)	Proposed model (model 2)
Absolute indices	χ2/df	<6	6.242	4.768
	RMR	<0.05	0.036	0.055
	RMSEA	<0.08	0.088	0.074
Relative indices	CFI	>0.90	0.923	0.883
	GFI	>0.90	0.905	0.859
	NFI	>0.90	0.910	0.857
	RFI	>0.90	0.889	0.838
	IFI	>0.90	0.923	0.884
	TLI	>0.90	0.905	0.868
Parsimony indices	PGFI	>0.50	0.638	0.703
	PNFI	>0.50	0.740	0.757
	PCFI	>0.50	0.751	0.780

of satisfactory discriminant validity. In addition, the square root of the AVE of each construct was greater than the correlation coefficients among constructs, further confirming the discriminant validity of the measures (Lee et al., 2015).

4.3 Structural model and hypothesis testing

The structural model indicated that there was no multicollinearity in any of the variables. Among the R^2 values of the dependent variables, the value for environmentally friendly behaviours was 0.52; that for environmental concern behaviours was 0.45; that for sustainable behaviours was 0.46; that for mental involvement was 0.46; and that for norm arousal was 0.42. In addition, although other indicators did not reach the standard value, they were very close (Table 3). Therefore, the proposed model fit the data acceptably: $\chi 2/df = 4.768$, $p < 0.01$, RMSEA = 0.074, PGFI = 0.703, PNFI = 0.757, PCFI = 0.780.

The findings indicated that sensory experience positively affected mental involvement ($\beta = 0.64$, $p < 0.001$), and mental involvement significantly affected norm arousal ($\beta = 0.61$, $p < 0.001$). However, there was a nonsignificant relationship between sensory experience and norm arousal. Thus, Hypotheses 1a and 1c were supported, while Hypothesis 1b was not. Sensory experience was statistically significant in predicting environmentally friendly behaviours ($\beta = 0.23$, $p < 0.001$), environmental concern behaviours ($\beta = 0.21$, $p < 0.001$) and sustainable behaviours ($\beta = 0.24$, $p < 0.001$), which supported Hypotheses 2a, 2b and 2c. Mental involvement did not significantly impact environmental concern-based behaviours, while there was a significant positive relationship between mental involvement and environmentally friendly behaviours ($\beta = 0.31$, $p < 0.001$); thus, Hypothesis 3a was supported, while Hypothesis 3b was not. It is worth noting that there was a significant negative relationship between mental involvement and sustainable behaviours ($\beta = -0.40$, $p < 0.001$); hence, Hypothesis 3c was not supported. Additionally, the results showed that there was a significant positive relationship between norm arousal and environmentally friendly behaviours ($\beta = 0.30$, $p < 0.001$), environmental concern-based behaviours ($\beta = 0.78$, $p < 0.001$) and sustainable behaviours ($\beta = 0.55$, $p < 0.001$). Thus, Hypotheses 4a, 4b and 4c were also supported. An overview of the research model and achieved results are depicted in Figure 2.

4.4 Spillover effects among experiences

The results indicated that the spillover effects among tourists' experiences model (Model 1) fit the data acceptably: χ2/df = 6.242, $p < 0.01$, CFI = 0.847, PGFI = 0.586, PNFI = 0.658, PCFI = 0.667 (Table 4). Additionally, model 1 showed the predictive power of mental involvement and norm arousal; 45.0% of mental involvement can be explained by sensory experience, and 41.0% of norm arousal can be explained by sensory experience and mental involvement. Thus, there were spillover effects among tourists' experiences.

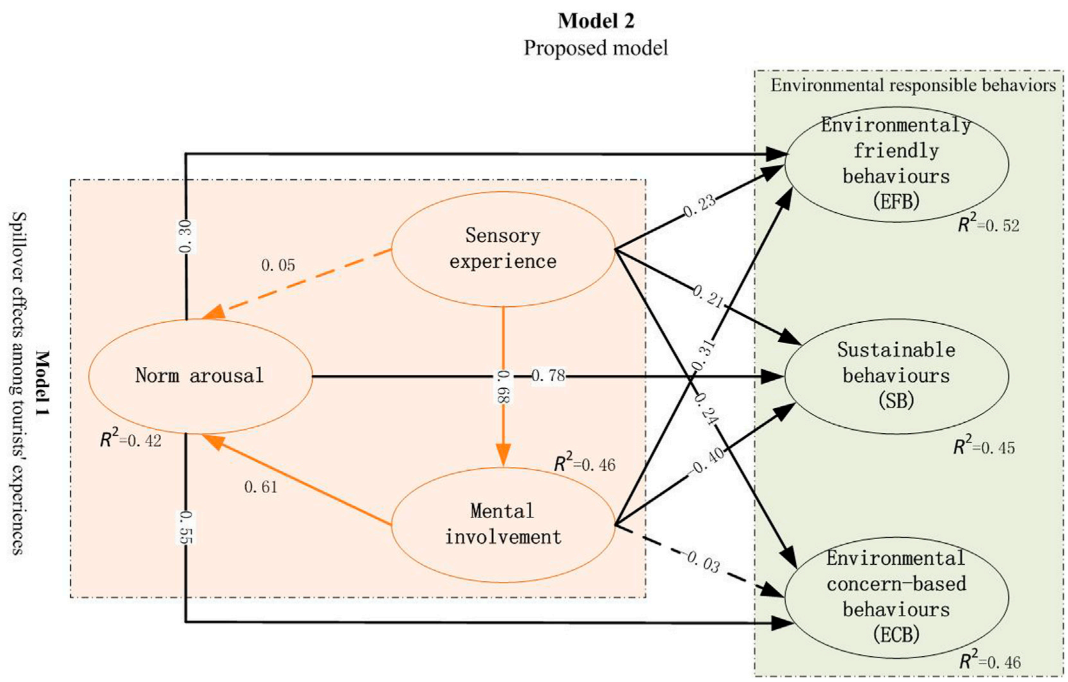

FIGURE 2
Results of the structural model.

4.5 Mediating effects of mental involvement and norm arousal

We adopted bootstrapping to test the mental involvement and norm arousal construct regarding its mediating role in the conceptual model. A 95% confidence interval (CI) of the parameter estimates was obtained by bootstrapping (n = 5,000).

4.5.1 Model 1: Mediating effects of mental involvement

Sensory experience was set as an independent variable; mental involvement was set as the mediating variable; and norm arousal was the dependent variable. We clarified the influence of tourists' sensory experience on their norm arousal, and mediation was examined. The results are provided in Table 4. The mediation relationship was statistically significant based on the bootstrapping results: $b_{sensory\ experience\ -mental\ involvement\ -norm\ arousal}$ = 0.499 not including zero at the 95% CI, with the lower limit CI (LLCI) and the upper limit CI (ULCI, Table 4). Additionally, the direct relationship of sensory experience with norm arousal was statistically nonsignificant: b = 0.070, including zero at 95% CI, LLCI = −0.089, ULCI = 0.257 (Hayes, 2017). The results supported the idea that mental involvement completely mediates the relationship between sensory experience and norm arousal. The details of the results can be found in Table 4.

4.5.2 Model 2: Mediating effects of mental involvement and norm arousal

Sensory experience was set as an independent variable; mental involvement was set as the mediating variable; and ERB was the dependent variable. We clarified the influence of tourists' sensory experience on their ERBs, and mediations were examined. The mediation relationship was statistically significant based on the bootstrapping results: bsensory experience-mental involvement-EFB = 0.232, not including zero at the 95% CI, with the lower limit CI (LLCI) and the upper limit CI (ULCI, Table 4). Additionally, the direct relationship of sensory experience on EFB was statistically significant: b = 0.261, also not including zero at 95% CI, LLCI = 0.110, ULCI = 0.357 (Hayes, 2017). The results supported the idea that mental involvement partly mediates the relationship between sensory experience and EFB. The details of the results can be found in Table 4. The mediation relationship was statistically nonsignificant based on the bootstrapping results: bsensory experience-mental involvement - ECB = 0.020, colluding zero at the 95% CI, with the lower limit CI (LLCI) and the upper limit CI. The mediation relationship was statistically significant based on the bootstrapping results: bsensory experience-ECB = -0.295 not including zero at the 95% CI. The direct relationship of sensory experience on ECB was statistically significant: b = 0.232, also not including zero at 95% CI, LLCI = 0.107, ULCI = 0.414 (Hayes, 2017).

TABLE 4 Mediating effects of mental involvement and norm arousal in Models 1 and 2

Model	Path	Point estimate	Product of coefficients		Bootstrap 5,000 time 95% CI (Percentile)		P
			SE	Z	Lower	Upper	
Model 1	**Mediating effects of mental involvement**						
	Indirect effect: Sensory experience→ mental involvement→ norm arousal	0.499	0.062	8.048	0.392	0.633	0.000
	Direct effect: Sensory experience→ norm arousal	0.070	0.089	0.788	-−0.089	0.257	0.416
	Total effects	0.569	0.084	6.762	0.406	0.735	0.000
Model 2	**Mediating effects of mental involvement**						
	Indirect effect: Sensory experience→ mental involvement→ EFB	0.232	0.063	3.683	0.110	0.357	0.001
	Direct effect: Sensory experience→ EFB	0.261	0.079	3.304	0.126	0.432	0.001
	Total effects	0.493	0.082	6.012	0.344	0.663	0.000
	Indirect effect: Sensory experience→ mental involvement→ SB	−0.295	0.083	-3.554	-−0.488	−0.166	0.000
	Direct effect: Sensory experience→ SB	0.232	0.078	2.974	0.107	0.414	0.001
	Total effects	−0.063	0.049	-1.286	-0.170	0.023	0.150
	Indirect effect: Sensory experience→ mental involvement→ ECB	−0.020	0.064	-0.313	−0.159	0.095	0.168
	Direct effect: Sensory experience→ ECB	0.236	0.064	3.688	0.151	0.401	0.000
	Total effects	0.216	0.058	4.069	0.127	0.355	0.001
	Mediating effects of mental involvement and norm arousal						
	Indirect effect: Sensory experience→ mental involvement→ norm arousal→ EFB	0.141	0.036	3.917	0.078	0.220	0.000
	Direct effect: Sensory experience→ EFB	0.261	0.079	3.304	0.126	0.432	0.001
	Total effects	0.402	0.087	4.621	0.250	0.588	0.000
	Indirect effect: Sensory experience→ mental involvement→ norm arousal→ SB	0.353	0.068	5.191	0.236	0.502	0.000
	Direct effect: Sensory experience→ SB	0.232	0.078	2.974	0.101	0.405	0.001
	Total effects	0.585	0.125	4.680	0.372	0.869	0.000
	Indirect effect: Sensory experience→ mental involvement→ norm arousal→ ECB	0.238	0.048	4.958	0.156	0.343	0.000
	Direct effect: Sensory experience→ ECB	0.256	0.064	4.000	0.151	0.401	0.000
	Total effects	0.494	0.091	5.418	0.338	0.693	0.000

Thus, mental involvement partly mediated the relationship between sensory experience and ECB.

Sensory experience was set as an independent variable; mental involvement and norm arousal were set as the mediating variables; and ERB was the dependent variable. We clarified the influence of tourists' sensory experience on their ERBs, and multiple mediations were examined. The mediation relationship was statistically significant based on the bootstrapping results: bsensory experience-mental involvement-norm arousal-EFB = 0.141, bsensory experience-mental involvement-norm arousal-SB = 0.353 and bsensory experience-mental involvement-norm arousal-ECB = 0.238, not including zero at the 95% CI, with the lower limit CI (LLCI) and the upper limit CI (ULCI, Table 4). The results supported the idea that mental involvement and norm arousal play a mediating role in the relationship between sensory experience and norm arousal. The details of the results can be found in Table 4.

5 Discussion and conclusion

5.1 Theoretical implications

Tourists' environmentally responsible behaviours are important to natural resources and environmental protection and ensure sustainability in nature reserves (Zhang et al., 2020). Therefore, activating tourists' ERBs is critical to mitigating the negative impacts of tourism on the natural environment. However, the causes of tourists' ERBs are complex, and there are many factors influencing ERBs (Lin et al., 2022). Studying the relationship between tourists' experiences and ERBs is useful to meet the needs of tourists and protect the environment in nature reserves. Although some scholars have studied the relationship between tourists' experiences and ERBs (Rosa and Collado, 2019; Wu et al., 2022), few have theorised and empirically validated the cognitive advancement process among tourists' experiences and the relationship between these experiences and distinct dimensions of ERBs. This study thus contributes to this body of knowledge by building a theoretical framework for various dimensions of experience, leading to the identification of distinct ERBs and mediating effects. It also proves that not all dimensions of tourists' experiences positively influence ERBs.

This study calls for a more nuanced understanding of tourists' experiences by adopting Lee's (2015) and Xu's (2018) scales. The dimensions of our experiential scale are different from those found in previous studies; indeed, we include sensory experience, mental involvement and norm arousal. The present research extends the existing studies on tourists' experience by affirming the predictive role of sensory experience on mental involvement and the predictive effect of mental involvement on norm arousal. Additionally, we found that mental involvement fully mediates the relationship between sensory experience and norm arousal. These findings underscore the need for a more careful study of the structure of tourists' experiences and the complex relationships that exist among these experiences. We conclude that through sensory experience, individuals gain a more in-depth recreational experience leading to their physical and mental enjoyment. Moreover, only on this basis will individuals engage in ecological observation, reflect on their behaviours and reach normative awakening. Sensory experience is essential in the tourist experience, and norm arousal is ranked the highest in the hierarchy of tourist experiences. Sensory experience can activate norm arousal only through mental involvement. Our research proves that Maslow's hierarchical needs theory is also applicable in the field of recreational experience. At the same time, it also proves that there is a spillover effect among tourists' experiences.

Although prior research has extensively studied the associations between tourists' expectations and ERB, the present research extends this body of knowledge by segmenting experiences and ERB dimensions into a research model. The results of our study partly affirm the promotion of tourists' experiences, which is consistent with the conclusions found in previous studies (Duerden and Witt, 2010; Lee et al., 2015; Wu et al., 2022). Tourists' experiences affect their behaviours in relation to environmental conservation in nature-based tourism destinations. A tourist with a high level of sensory experience as well as norm arousal is more likely to engage in environmentally friendly behaviours, behave out of his or her concern for the environment and engage in sustainable behaviours. However, mental involvement only positively affects environmentally friendly behaviours and has no effect on behaviours related to environmental concerns. It is worth noting that the higher the level of mental involvement is, the more reluctant tourists are to engage in sustainable behaviours. This discovery differs from the results found in previous studies (Lee et al., 2015). This particular finding further underscores the necessity to consider the driving mechanism of different dimensions of tourists' experiences to identify distinct ERBs within an integrated model. Additionally, this finding highlights the need to identify and assess possible negative relationships between mental involvement and sustainable behaviours.

Furthermore, the present study also provides a more in-depth view into the mechanisms that influence the formation of ERBs by examining the role of mental involvement and norm arousal as mediating factors between sensory experience and ERBs in our research model. We find that mental involvement partly mediates the relationship between sensory experience→ environmentally friendly behaviours and sensory experience→ sustainable behaviours. We also find that mental involvement and norm arousal partly mediate the relationship between sensory experience→ environmentally friendly behaviours, sensory experience→environmentally concerned behaviours and sensory experience→sustainable behaviours. We conclude that the primary experience (sensory experience) of tourists can not only directly affect their ERBs but also influence their ERBs by stimulating a higher hierarchy experience (mental involvement and norm arousal) in nature reserves.

5.2 Managerial implications

From a practical perspective, the findings of this study provide important insights into sustainable development for tourism developers and nature reserve managers. The findings provide policymakers with a better understanding of the complex structure of tourists' experiences. It is worth remembering that mental involvement has a significant fully mediating effect on the relationship between sensory experience and norm arousal. This fact should remind policymakers that they should focus first on fostering tourists' primary experiences. Therefore, it is important to protect the biodiversity of protected areas, maintain a superior ecological environment quality, protect landscape integrity, and coordinate the planning of infrastructure and the surrounding environment. These factors play a decisive role in tourists' first impression, which leads to their most intuitive primary experience.

The influence of tourists' experiences on their ERBs has been confirmed, suggesting that improving the experience (except for the mental involvement dimension) that prompts tourists to engage in ERBs could be an appropriate intervention. We find that engaging in ERBs largely depends on the primary and advanced experience; when people initially enjoy natural landscapes visually or when their experience leads them to engage in ecological observation and to reflect on their behaviour, they are more likely to engage in ERBs. If tourists are excessively immersed in an enjoyable experience that is brought about by the natural environment, they will not pay attention to environmental protection in the nature reserve or will not even stop others from interfering with the environment or pick up garbage to avoid unpleasant experiences for themselves.

This finding reveals that mental involvement and norm arousal significantly mediate the relationship between sensory experience (primary hierarchy experience) and ERBs. Managers should encourage tourists to have experiences that are ranked higher in the hierarchy by combining online and offline methods and reduce the negative impact on some ERBs caused by tourists' excessive immersion in the middle hierarchy experience. Thus, introducing tourists to the landscape formation process and making them ecologically sensitive to the nature reserve require educational films, advertisements, pedagogy and other tools to help tourists redirect their experience, reflect on their own environmental behaviours, and engage in ecological thinking and observation. Meanwhile, organizing activities such as hiking, camping, and environmental education workshops can also help tourists to improve their environmental awareness so they awaken to normative environmentalism. We emphasise that nature reserves should strengthen the supervision of tourists' behaviours. In high-quality landscape areas, warning signs and penalties should be established. Furthermore, combining electronic interpretation with soundscapes and educating tourists on the environment without interfering with their experience is also a feasible measure to upgrade tourists' mental experiences and to stimulate the implementation of ERBs.

5.3 Limitation and further research

The model constructed in this study is an empirical study of only the Nanlin National Nature Reserve. In the future, it needs to be verified in other types of protection areas. At the same time, our research variables use only experience and tourists' ERBs. In the future, we can embed experience factors into models such as theory of planned behaviour, value-belief-norm theory *etc.* to explain tourists' ERBs. In addition, the numbers of samples collected in the 2 years were very different, so we can further study whether there are differences in the relationship between tourists' experience and their ERBs in different seasons.

6 Conclusion

This study explores the relationship between the use and conservation of natural resources *via* tourists' experiences and ERBs. It reveals that tourists' experiences are hierarchical and sensory experience can activate mental involvement only through norm arousal. Second, not all dimensions of experience have a positive impact on behaviour. If tourists' experiences are limited to mental involvement, which may not be conducive to eco-environmental conservation in the protected areas. In addition, there is a mediating effect of higher hierarchy experiences (norm arousal) on the relationship between primary hierarchy experiences (sensory experience) and tourists' ERBs. The present research extends this body of knowledge by segmenting experiences and ERB dimensions into a research model. It opens the field for future research paths in the exploration of the paradox that emerges out of the natural experience and tourists' ERBs and provides insights into and points to ecological implications for reserve managers and tourism operators.

Data availability statement

The original contributions presented in the study are included in the Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

Writing the initial draft, YZ; Conceptualization and methodology, RC; Visualization, investigation, and data curation, XX, Project administration, JY; Software and Validation, YG; Formal analysis and Supervision, ZW; Conceptualization, Writing—Review and Editing, SL; Formal analysis, CZ. All authors have read and agreed to the published version of the manuscript.

Funding

This work was supported by the National Natural Science Foundation of China [42171242,42271206,42271250]; GDAS′ Project of Science and Technology Development [2020GDASYL-20200104007]; Natural Science Foundation of Guangdong Province [2021A1515011073]; High-level Talents and Lingnan Scholars' Research Start-up Project of Foshan University [CGZ07001].

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.1028508/full#supplementary-material

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frontiers | Frontiers in Environmental Science

TYPE Policy and Practice Reviews
PUBLISHED 19 October 2022
DOI 10.3389/fenvs.2022.1017923

OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Environmental Economics and Management,
a section of the journal Frontiers in Environmental Science

RECEIVED 12 August 2022
ACCEPTED 13 September 2022
PUBLISHED 19 October 2022

CITATION
Yang Y, Jianmin Z, Yaya H and Xiaoxuan K (2022), Economic and ecological benefit evaluation of geothermal resource tax policy in China. *Front. Environ. Sci.* 10:1017923.
doi: 10.3389/fenvs.2022.1017923

Economic and ecological benefit evaluation of geothermal resource tax policy in China

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Geothermal energy is a renewable energy source, and geothermal heating is a livelihood project, so a resource tax can protect resources and regulate prices. Reasonable geothermal energy resource tax collection standards are conducive to high-quality industrial development. This paper takes 15 provinces and cities that clearly levy geothermal resource taxes in China as the research object, constructs an System Dynamics model of geothermal resource tax, and studies the impact of geothermal resource tax on the income of geothermal enterprises and CO_2 emission reduction. Then, the forecast simulates the economic and environmental benefits brought about by the use of geothermal resources from 2021 to 2035. The research results show that using geothermal resources for heating can significantly reduce CO_2 emissions, and the higher the proportion of geothermal use is, the greater the CO_2 emission reduction before 2035. The fifteen provinces and cities that clearly levy geothermal resource taxes will find it difficult to achieve corporate profits at the current residential heating utilization price and geothermal energy resource tax rate; that is, to achieve a balance of income and expenditures for geothermal enterprises without financial subsidies, the price of geothermal heating will be significantly higher than the heating price of traditional central heating and the price of electric self-heating.

KEYWORDS

geothermal energy, resource tax, carbon emissions, heating economy, ecological benefit

1 Introduction

The United Nations Intergovernmental Panel on Climate Change (IPCC): Geothermal resources are the second largest clean energy in the world and can be directly used for heating, hot water, hot springs, *etc.* At the same time, geothermal energy, as a clean and renewable energy source such as solar energy and wind energy, has significant emission reduction benefits. The development and utilization of geothermal resources can alleviate the crisis of energy shortages, increase the proportion of non-fossil energy use, and promote the construction of urban ecological civilization (Luo and Ren, 2021). China's geothermal resources account for approximately one-sixth of the world's geothermal resources. In recent years, driven by the trend of clean heating in the north, geothermal development and utilization have begun to develop rapidly. Especially in areas rich in geothermal resources, geothermal energy has become one of the main sources of central heating. However, the government not only subsidizes the geothermal industry relatively little but also imposes a resource tax.

Resource tax is a tax policy tool levied on taxable natural resources that aims to adjust the difference between income and resource levels and improve the efficiency of resource development and utilization. The current geothermal development technology is mainly based on “hydrothermal type” mid-deep geothermal, that is, heat is obtained by pumping and irrigating deep groundwater. Therefore, when formulating the detailed rules for the collection of geothermal resources tax, all localities take the amount of water as the tax basis. Specifically, by sorting out the policies of various regions, it can be concluded that most of the regions implement the taxation method based on water consumption, which is classified by the use of geothermal water, but the specific standards are significantly different. For example, the general-purpose geothermal water tax rate in Beijing is 8.5 ¥/m^3, the consumption-type geothermal water (such as hot springs, bathing, *etc.*) is 30 ¥/m^3, and the recharge type is 1 ¥/m^3; the consumption-type geothermal water in Henan Province is 12 ¥/m^3, and the recharge type is 1 ¥/m^3; the consumption-type geothermal water in Hebei Province is 30 ¥/m^3, and the recharge type is 2 ¥/m^3; southern regions such as Zhejiang and Jiangsu do not distinguish between uses, and each cubic meter of geothermal water is charged 3 ¥ and 10 ¥, respectively. The collection of resource tax can not only protect resources and adjust prices but also solve the intergenerational problem of resources. This means that it makes the development, utilization and allocation of natural resources more reasonable and effective, and at the same time, it can also promote local economic development and turn resource advantages into economic advantages.

The starting point of geothermal heating is clean heating, which is consistent with the original intention of the resource tax. However, the specific impacts of sustainability programs for clean heating are often clouded by the confounding effects of multiple socioeconomic, policy and environmental factors operating concurrently (Bryan et al., 2018). At present, the primary task of China’s geothermal enterprises is to meet the heating needs of the people, but when the tax revenue exceeds the enterprise’s ability to bear, they will inevitably fall into the predicament of survival, and other goals, such as achieving clean heating, will not be achieved. For example, in some northern regions, it is not uncommon for geothermal heating costs to be flat or even lower than that of ordinary coal-fired boilers, so that some projects are even operating at a loss. In other words, if preferential policies have not been fully implemented and high new taxes are levied on them, it is inevitable that the geothermal industry will not be able to bear the burden.

Nations require globally coordinated, national-scale, comprehensive, integrated, multisectoral analyses to support national target setting that prioritizes efficient and effective sustainability interventions across societies, economies and environments (Gao and Bryan, 2017). Reasonable geothermal energy resource tax collection standards are conducive to the sustainable and high-quality development of the industry. This paper takes the resource tax of geothermal energy as the research object and aims to analyze its reasonable charging standard and its influence on the optimization of the regional energy structure. This research has important practical significance for perfecting the formulation of resource tax policy. This paper focuses on the areas where geothermal resource taxes are currently levied nationwide. As of 2020, 15 provinces and cities in China, including Beijing, Henan, Zhejiang, Shanxi, Guangdong, Jiangsu, Jiangxi, Anhui, Hunan, Tianjin, Chongqing, Gansu, Inner Mongolia, Ningxia and Guangxi, have clarified the applicable tax rates for geothermal resources. That is, 15 provinces and cities are the research scope of this paper. Based on system dynamics, this paper establishes a geothermal resource tax model including the enterprise benefit subsystem, environmental benefit subsystem, regional economic subsystem and tax policy effect subsystem. The model simulates and analyses the impact of changes in the tax rate of geothermal resources on the economic benefits of geothermal enterprises to explore the price of geothermal energy and the reasonable collection standard of geothermal energy resource tax. This will provide a reliable basis for governments at all levels to scientifically formulate reasonable tax rates for geothermal energy resources and realize the rational development and utilization of geothermal resources. This research has important theoretical value for improving the relevant theories of resource economics and has important practical significance for improving resource tax policy formulation.

2 Literature review

In the related research of geothermal energy, many domestic and foreign scholars have made some contributions. Research on development and utilization. New Zealand has achieved 100% renewable electricity systems, with geothermal generation accounting for 12–14% (Mason et al., 2010). The exploitation of geothermal resources has an impact on the biological, chemical and physical characteristics of groundwater and the subsurface (Stefanie et al., 2013). Xi’an developed and utilized geothermal resources in the early days, resulting in problems such as ground subsidence and a rapid decline in the groundwater level (Feng, 2017). China’s geothermal energy industry system has shown its embryonic form. In the past 10 years, the direct utilization of hydrothermal geothermal energy in China has increased at an average annual rate of 10% (Zhou, 2018). The scientific development of geothermal energy is a reasonable choice to effectively alleviate energy shortages in Beijing, realize energy structure adjustment, build a safe, stable, clean and high-quality energy supply system, and cope with climate change (Qiang, 2018). Research on development potential. The development potential of deep geothermal energy and shallow geothermal energy resources in Beijing is large, and the utilization prospects are very broad (Huang et al., 2016). Payam stated that geothermal energy is an important potential and strategic area for renewable energy development and future research activities (2020). The production and consumption of national geothermal energy is one of the world's top priorities, helping to reduce CO2 emissions in the atmosphere and air pollution levels (Chen, 2020). By 2030, 19.25% of the Chinese urban heating area will be provided by ground source heat pumps, which have great development potential (Wang et al., 2021).

Research on Resource Taxation Policy. Taking the geothermal hot springs in Yi Chun City as an example, Huang, G. R studied the collection of geothermal resource taxes (2013). Sam, M., and Basil, S. analyzed the sustainability of geothermal resource use in New Zealand using resource taxes rather than royalties (2015). It is actively suggested that the guiding and supporting functions of tax policies be used to promote the rational development and utilization of geothermal resources and setting different collection rates for geothermal resources for different purposes (Wu et al., 2016a). China needs to expand the scope of taxation of resource taxes and includes geothermal resources in the scope of regulation and control of resource taxes (Pan, 2017). The formulation of differentiated resource tax rates can effectively control the supply and demand of depletable resources, play a positive role in industrial restructuring, and coordinate regional economic development (Qiao, 2018). Tianjin Municipality takes 40°C as the temperature limit and determines the collection method (water resource tax or geothermal resource tax) according to the temperature level (Zhang and Li, 2021).

In summary, the development potential of the geothermal energy industry at home and abroad is very large. Geothermal resources were brought into the scope of resource tax collection in foreign countries earlier. However, there is no consensus in the academic community on the collection standards of geothermal energy resource taxes and the impact of geothermal energy resource taxes on energy structure optimization. Moreover, in the actual development process of the Chinese geothermal energy industry, there are still some problems, for example, the lack of implementation clauses and implementation rules for the relevant laws and regulations supporting geothermal energy fiscal and tax. The rationality of expropriation has been questioned by scholars. Compared with other clean energy industries, such as solar energy, the supportive policy of the geothermal energy industry is insufficient, and incentive policy standards such as preferential tax rates and subsidies are not unified and clear, which inhibits the high-quality development of the geothermal heating industry.

3 Data sources and methods

3.1 Data collection and accounting

This article collects relevant data from the following yearbooks: 2005–2019 *"Beijing Statistical Yearbook"* and other provinces and cities' yearbooks, 2005–2019 *"China Statistical Yearbook"*, 2005–2019 *"Urban Planning Yearbook"*, 2005–2018 *"Land and Resources Bulletin"*, *"Statistical Bulletin of China's Land, Mineral and Marine Resources in 2017"*, *"Statistical Bulletin of China's Marine Economy in 2019"*, *"Clean Heating Plan in winter in Northern Region (2017–2021)"*, *"Thirteenth Five-Year Plan for Geothermal Energy Development and Utilization"*, *"Thirteenth Five-Year Plan for Renewable Energy Development"*, *"China Mining Resources Report 2019"*, *"China Mining Resources Report 2020"*, *etc.* In addition, some data were obtained from the official website, such as geothermal heating prices and geothermal resource tax rates. The relevant websites are from the provincial and municipal urban management committees, the provincial and municipal development and reform commissions, the National Development and Reform Commission, the National Bureau of Statistics, Provincial and municipal finance bureaus, carbon trading platform websites, *etc.* The data of other provinces and cities are also collected in the statistical yearbooks of the provinces and cities in each year, as well as in the relevant documents released, and some are collected from the official websites of the provinces and cities. Detailed data are shown in Tables 1–3. Based on residential heating area and total population data, a unitary regression equation between the provinces and cities in the central heating area is constructed, as shown in Table 4 (Note: Details of Tables 1–4).

This article assumes that the government and geothermal companies have no original investment. The learning rate of photovoltaic power generation costs in Northwest China from 2010 to 2015 was between 18% and 30% (Li and Sun, 2017). The learning rate of photovoltaic power generation costs varied from 15% to 25% from 2005 to 2010 (Sui, 2012). Due to the lack of relevant data of geothermal enterprises and the development and utilization of geothermal later than photovoltaic power generation, the hypothesis is made based on the learning rate of photovoltaic power generation cost. Suppose the cost learning rate for geothermal heating is 10%. This means that if the growth rate of geothermal development investment is greater than 0.1, the geothermal heating investment cost will decrease by 10%; otherwise, the geothermal heating investment cost will remain unchanged. The calculation of CO_2 emissions in central heating

TABLE 1 Relevant data indicators and basis.

Related indicators	Setting basis
The geothermal enterprise learning rate is 10%	(Pan, 2017; Qiao, 2018)
The carbon trading price is 61.69 ¥/t	Beijing Electronic Trading Platform for Carbon Emission Rights (bjets.com.cn)
The CO_2 emission factor of standard coal is 2.499	United Nations Intergovernmental Panel on Climate Change (IPCC)
The unit investment cost of geothermal heating is 204.9 ¥/m^2	(Wu et al., 2016b)
Geothermal heating unit operation and maintenance cost 13.55 ¥/m^2	(Wu et al., 2016b)
CO_2 emission reduction per unit of geothermal heating is 24.5 kg/m^2	(People's Government of Jiangxi Province, 2020)

TABLE 2 Relevant input data in central heating areas.

Region	Proportion of geothermal resources used (2019)	Is recharge technology used	Geothermal heating resource tax rate (¥/m^3)	Recharge resource tax rate (¥/m^3)	Heating price (¥/m^2)
Beijing	8% (Proportion of geothermal heating)	yes	8.5 (Gansu Daily, 2021)	1 (Gansu Daily, 2021)	30 (Zhang and Li, 2021)
Tianjin	3.86%	yes	3 (Central heating charge notice, 2021)	1 (Central heating charge notice, 2021)	Resident: 25 Nonresidents:40 (Li and Sun, 2017)
Inner Mongolia Autonomous Region	0.4% (Proportion of clean heating)	no	10 (Hualv.com, 2021)	—	18.4 (Sui, 2012)
Gansu Province	20%	yes	3 (Hualv.com, 2022a)	—	(Lanzhou)7.5 (Gansu Daily, 2021)
Ningxia Hui Autonomous Region	4.4% (2018)	no	12 (Hualv.com, 2022b)	—	24.5 (Jiang, 2020)
Shanxi Province	1.62%	yes	10 (Hualv.com, 2022c)	1 (Hualv.com, 2022c)	24 (Xinhua News Agency, 2020)
Henan Province	9.5%	yes	12 (NewEnergy.IN-EN.com, 2020)	1 (NewEnergy.IN-EN.com, 2020)	22.8 (Mei, 2021)

TABLE 3 Relevant input data in non-central heating areas.

Region	Proportion of geothermal resources used (2019)	Geothermal heating resource tax rate (¥/m^3)	Heating price (¥/m^2)
Zhejiang Province	16% (2015)	3 (Tianjin Municipal Tax Service, State Taxation Administration, 2020)	—
Jiangsu Province	11%	10 (Inner Mongolia Daily, 2020)	Resident:8.01 Nonresidents:11.94 (Bendibao.com, 2021b)
Jiangxi Province	11%	0.6 (Chen, 2020)	—
Anhui Province	8%	2 (Ningxia Daily, 2020)	9.5 (Bendibao.com, 2020a)
Hunan Province	2.5%	3 (Shanxi Provincial Tax Service, State Taxation Administration, 2020)	—
Chongqing city	15%	2 (Henan Provincial Tax Service, State Taxation Administration, 2020)	—
Guangdong Province	26.7%	1 (Zhejiang Provincial Tax Service, State Taxation Administration, 2020)	—
Guangxi Zhuang Autonomous Region	25%	4 (Department of Finance of Jiangsu Province, 2020)	—

TABLE 4 Regression equation of total population and residential heating area in other areas of central heating area.

Region	Regression equation (Y represents residential heating area, X represents total population)
Beijing	Y = 33.19X-31958.23 (R^2 = 0.94, T = 12.57)
Tianjin	Y = 99.09X-109976.9 (R^2 = 0.72,T = 5.17)
Inner Mongolia Autonomous Region	Y = 546.36X-132665.1 (R^2 = 0.99,T = 44.96)
Gansu Province	Y = 162.73X-406029.6 (R^2 = 0.95,T = 11.85)
Ningxia Hui Autonomous Region	Y = 148.46X-88712.90 (R^2 = 0.95,T = 11.02)
Shanxi Province	Y = 222.86X-767938 (R^2 = 0.86,T = 6.67)
Henan Province	Y = 85.61X-888724.3 (R^2 = 0.94,T = 10.20)

Modify the description.

areas requires the following data. In each heating season, geothermal heating can replace 9,710 tons of standard coal or 1,080 m^3 of natural gas per 1 million m^2 of buildings. It can also reduce CO_2 emissions by 24,500 tons, SO_2 emissions by 228 tons, NO_X emissions by 151 tons, particulate matter emissions by 416 tons, and smoke and dust by $1.3*10^8$ m^3, increasing electricity sales by 30 million kWh ($1.5*10^8$ ¥) and adding 400 jobs (Pang et al., 2020). Therefore, every 10,000 m^2 of the heating area can be converted into 97.1 tons of standard coal, and every 10,000 m^2 of the heating area can reduce CO_2 by 245 t. After consulting the Beijing carbon trading platform, the average price of carbon trading in Beijing in 2019 was 7.81 euros/ton, approximately 61.69 ¥/t. In areas where geothermal water is approximately 50°C, 2 m^3 of geothermal water needs to be pumped per square meter of heating area, so the resource tax can be calculated based on the amount of geothermal water.

The collection of geothermal resource taxes could have a great range of impacts, including geothermal resource exploitation, government taxation, and greenhouse gas emissions. This paper establishes a taxation model of geothermal energy resource taxes, including SD models of the enterprise benefit subsystem, environmental benefit subsystem, regional economic subsystem, and tax policy effect subsystem. The model is used to study the impact of geothermal resource taxes on geothermal heating prices and the impact of geothermal prices on the economy and other subsystems. The causality diagram of this model is shown in Figure 1.

3.2 Build subsystems based on factors

3.2.1 Enterprise benefit subsystem

The enterprise benefit subsystem studies the corresponding benefits obtained by the geothermal enterprise. Assuming that the total population of the area is increasing at a certain growth rate and the demand for geothermal heating correspondingly increases, geothermal development and utilization will also increase, which is conducive to the development of the geothermal industry. With the advancement of science and technology, the cost of geothermal investment will show a downwards trend, which will lead to an increase in revenue for geothermal enterprises. At the same time, the increase in geothermal utilization area promotes an increase in geothermal revenue. An increase in geothermal revenue promotes an

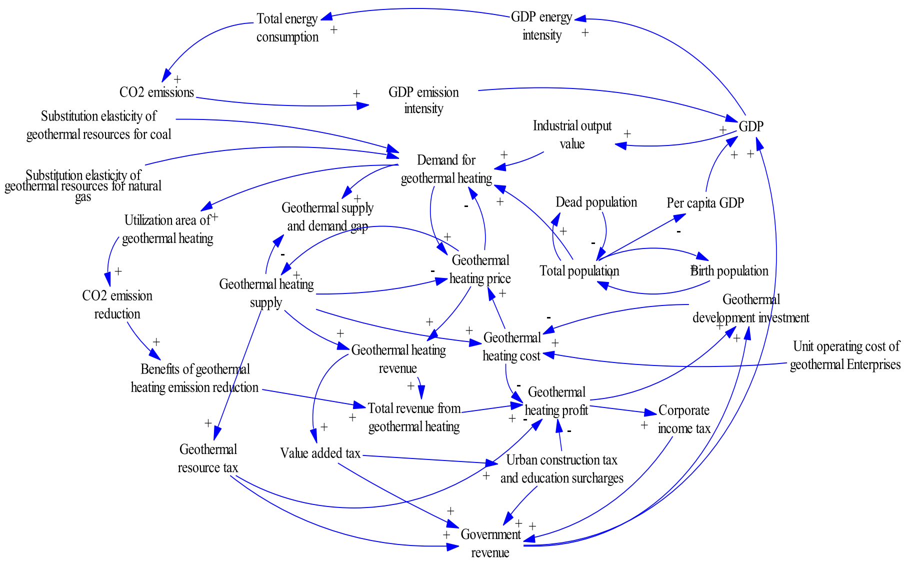

FIGURE 1
Causality of geothermal resource tax.

increase in corporate income tax, drives an increase in fiscal revenue, and affects the tax policy subsystem. The increase in the coverage of geothermal energy heating will lead to a reduction in the area of fossil energy heating, thereby reducing greenhouse gas emissions and affecting the environmental benefit subsystem.

The relevant indicators of the enterprise benefit subsystem include the geothermal heating utilization area, geothermal heating revenue, geothermal heating emission reduction revenue, geothermal heating price, geothermal heating cost, and geothermal resource tax rate.

1) The geothermal heating utilization area. This article believes that the geothermal heating utilization area has a linear relationship with the total population of the region. In this article, a unitary regression model with heating area as the explanatory variable and the total population of the region as the explanatory variable is constructed. The regression equation is shown in Eq. 1:

$$Y = ax + b \tag{1}$$

Y: the heating area of regional residential buildings; *x*: the total population of the region.

The geothermal heating utilization area is shown in Eq. 2:

$$Z = \lambda Y \tag{2}$$

Z: geothermal heating area; λ: proportion of geothermal heating area to total heating area.

2) Geothermal heating revenue.

$$W = c + Integ(N) \tag{3}$$

$$N = M - T \tag{4}$$

W: the cumulative net profit of geothermal heating; *c*: the initial value of the cumulative net profit of geothermal heating; *N*: the annual net profit of geothermal heating; *M*: the total profit of geothermal heating; *T*: the corporate income tax.

3) Geothermal heating emission reduction revenue

$$R_1 = R_{co_2} \times P_{co_2} \tag{5}$$

R_1: the income of geothermal heating emission reduction; R_{co_2}: the amount of CO_2 emission reduction;P_{co_2}: the carbon trading price.

4) Geothermal heating price. The price of geothermal heating is based on the residential heating price set by the provincial, municipal and city management committees as the benchmark price. According to the relevant policies of the Beijing Municipal Management Committee, the unit price of heating for residents in Beijing is 30 ¥/m^2, so this article uses 30 ¥/m^2 as the benchmark price.

5) Geothermal heating cost. The annual operation and maintenance costs of geothermal utilization include depreciation, water, electricity, labor, repairs, *etc.* The water fee is the price of water multiplied by the amount of water used, the electricity fee is the price of electricity multiplied by the amount of electricity used, the labor cost is wages times the number of people, and the maintenance cost is based on the proportion of fixed asset equipment. This article includes ground source heat pump heating and hydrothermal geothermal heating. It is known that the unit investment cost of the ground source heat pump is 197.6 ¥/m^2, and the operation and maintenance cost is 14.8 ¥/m^2 per year; the initial investment cost of the hydrothermal geothermal utilization area is 212.2 ¥/m^2, and the operation and maintenance cost is 12.3 ¥/m^2 per year (Jiang, 2020).

$$C = \frac{C_1 + C_2}{2} \tag{6}$$

C: the unit investment cost of geothermal heating; *Ct: the* unit investment cost of ground source heat pumps; C_2: the unit investment cost of hydrothermal geothermal heating, which is the average of the two. Operation and maintenance costs are obtained in the same way.

6) Geothermal resource tax rate. According to the resource tax rate table announced by each region, the geothermal resource tax rate can be obtained (for example, the resource tax rate announced by Beijing is 8.5 ¥/m^3).

3.2.2 Environmental benefit subsystem

In the environmental benefit subsystem, the utilization of geothermal resources will replace the utilization of fossil energy when heating the city and reduce the emission of the greenhouse gas CO_2. The increase in CO_2 emission reduction will affect the emission reduction revenue of geothermal heating and the enterprise benefit subsystem. The increase in CO_2 emissions reduction will accelerate the increase in investment in geothermal development, promote the development of the geothermal industry, and affect the benefit subsystem of geothermal enterprises. Moreover, the increase in CO_2 emissions will cause the government to invest more funds developing geothermal energy, reduce the investment cost of geothermal development, and affect the regional economic subsystem. In addition, the environmental benefits brought by geothermal resources will encourage the government to adopt various policies to encourage the development of geothermal enterprises. Tax policies should also be formulated to protect geothermal resources, prevent the excessive exploitation of geothermal resources, and affect the tax policy effect subsystem.

In this paper, indicators of the environmental benefit subsystem for central heating are CO_2 emission reduction and CO_2 emission reduction increase. Non-centralized heating uses indicators such as CO_2 emissions, CO_2 emissions increase, and CO_2 emissions reduction.

1) CO_2 emission reduction

$$R_{co_2} = d + Integ(r_{CO_2}) \tag{7}$$

R_{co_2}: the amount of CO_2 emission reduction; d: the initial value; r_{CO_2}: the increase amount of CO_2 emission reduction.

2) CO_2 emission reduction increase

$$r_{CO_2} = Z \times e \tag{8}$$

r_{CO_2}: the CO_2 emission reduction increase; Z: the area of geothermal heating;e: the CO_2 emission reduction per unit of geothermal heating.

The initial value d of CO_2 emission reduction is determined by the base year energy consumption and the CO_2 emission coefficient of standard coal. The formula is:

$$d = total\ energy\ consumption\ (10,000\ tons\ of\ standard\ coal)$$
$$\times\ CO_2 \text{ emission factor of standard coal}$$

3) CO_2 emissions

$$E_{co_2} = Integ(I_{co_2} - D_{co_2}) \tag{9}$$

E_{co_2}: the amount of CO_2 emissions;I_{co_2}: the CO_2 emissions increase; D_{co_2}: the CO_2 emissions decrease.

$$I_{co_2} = UE \times e_u \tag{10}$$

I_{co_2}: the CO_2 emissions increase; UE: the unit CO_2 emissions; e_u: the electricity consumption for heating.

$$D_{co_2} = Z \times e \tag{11}$$

D_{co_2}: the CO_2 emissions decrease; Z: the reduction in CO_2 emissions per unit of geothermal heating; e: the area used for geothermal heating.

3.2.3 Regional economic subsystem

The development of the regional economy is an important indicator that reflects the status of regional development. The use of geothermal resources enables geothermal enterprises to develop more rapidly and drives the development of the entire city's economy. At the same time, its use can reduce the import of resources and realize the green exploitation and utilization of local resources. An assumed increase in GDP would promote investment in geothermal development, increases in government expenditures, increases in subsidies for geothermal companies, and impacts on the corporate efficiency subsystem. An increase in GDP promotes an increase in energy consumption, which will increase greenhouse gas emissions and affect the environmental benefit subsystem. At present, government subsidies for the geothermal industry are realized through subsidies to geothermal companies, and price subsidies are given to geothermal companies to encourage them to develop the geothermal industry.

The relevant indicators of the regional economic subsystem include regional GDP, regional GDP growth rate, and regional geothermal heating development investment.

1) Regional GDP. Data were obtained according to the 2005–2019 statistical yearbooks of various regions.
2) Regional GDP growth rate. This article adopts a simplified method to calculate the average growth rate of GDP from 2005 to 2019 instead of the regional GDP growth rate.
3) Regional geothermal heating development investment. Regional geothermal heating development investment and related costs. The increase in investment in geothermal heating development is calculated based on GDP and government revenue; the proportion of R&D expenditure in government tax and GDP is calculated, and the two are added to obtain the increase in investment in geothermal heating development. This article assumes that all R&D funding investment is used for the development of the geothermal industry. The relevant formula is:

$$\delta = \alpha \times f_1 + \beta \times f_2 \tag{12}$$

δ: the increase in investment in geothermal heating development; α: GDP; β: government revenue; f_1: the average proportion of R&D expenditures in GDP from 2001 to 2018; f_2: the average proportion of R&D expenditures in government revenue from 2001 to 2018.

From the perspective of people's livelihood, there are more heating areas in the north, such as Beijing, Tianjin and Inner Mongolia. Although Inner Mongolia's regional GDP is much smaller than that of Beijing, the heating areas are similar.

3.2.4 The tax policy effect subsystem

The tax policy effect subsystem studies the changes in government taxes and revenues when resource tax rates change. Government revenue includes value-added tax, urban construction tax, geothermal resource tax, education surcharge and local education surcharge. The increase in fiscal and tax revenue increases GDP and affects the regional economic subsystem. The increase in fiscal and tax revenue allows the government to invest in the geothermal industry, thereby reducing the investment of the geothermal industry and promoting the increase in geothermal utilization area, which affects the enterprise benefit subsystem. The investment of the government in the geothermal industry increases the utilization area of geothermal resources, which drives the reduction in greenhouse gas emissions and affects the environmental benefit subsystem. The collection methods of resource tax are AD valorem and specific collection. The amount of resource tax payable is calculated based on the sales or sales volume multiplied by the tax rate of the corresponding resource. The levy of a resource tax will increase the price of resources and increase the cost of resource extraction and consumption, thereby reducing resource consumption, promoting the rational development of resources and improving the level of comprehensive utilization of resources.

Different tax rates or preferential taxation are set for different resource extraction areas. The formulation of such tax rates and preferential taxation policies gives miners the motivation to reduce the waste of resources, make comprehensive use of resources and protect the environment. There are many directions for the use of government taxation, but resource taxation will require special funds to be used for the exploitation and protection of related resources. At present, some places have not yet created special funds for special purposes. Therefore, the resource tax collected will be used in other ways, which will weaken the role of the resource tax in protecting the environment.

The related taxation subsystem includes urban maintenance, construction tax, value-added tax, corporate income tax, geothermal resource tax, education surcharge, local education surcharge, and government revenue. Assuming that all geothermal companies are located in the city, the urban maintenance and construction tax rate is 7%. The relevant calculation formula is as follows:

$$VAT = R_2 \times t_v \tag{13}$$

VAT: value-added tax revenue; R_2: geothermal heating revenue; t_v: the value-added tax rate.

According to the relevant provisions of *the value-added tax regulations*, the low tax rate of 9% for geothermal use is levied on value-added tax, which is = 9%.

$$UCT = VAT \times \mathrm{t}_u \tag{14}$$

UCT: urban maintenance and construction tax;t_u: the urban maintenance and construction tax rate, which is 7%.

$$ES = VAT \times \mathrm{t}_e \tag{15}$$

ES: education surcharge and local education surcharge;t_e: education surcharge and local education surcharge rate, which is 5%.

$$GRT = V \times \mathrm{t}_g \tag{16}$$

GRT: geothermal resource tax revenue; V: geothermal water consumption; t_g: geothermal resource tax rate.

$$T = (R_1 + R_2) \times \mathrm{t} \tag{17}$$

T: the corporate income tax;R_1: the income from geothermal heating emission reduction;R_2: the income from geothermal heating; t: the corporate income tax rate.

$$M = R_1 + R_2 - T - UCT - ES - GRT \tag{18}$$

FIGURE 2
Map of national heating areas.

M: the total profit of geothermal heating.

There are two methods for determining the tax rate of geothermal energy resources: determining tax revenue based on water resources and levying taxes based on thermal energy. At present, the 15 provinces and cities that clearly levy geothermal resource taxes all base these taxes on the consumption of water resources; only Tianjin proposes levying geothermal resource taxes based on heat, but the conditions are not yet met. In addition, for the use of geothermal resources using recharge technology, a lower tax rate is proposed, that is, 1 ¥/m^3.

3.3 Building models based on regions

China's heating boundary is located in the Qin Ling and Huai He Rivers near 33° north latitude, and the map of national heating areas is shown in Figure 2. According to the division of heating regions, the 15 provinces and cities that levy geothermal resource taxes are divided into two types: central heating areas and non-central heating areas.

3.3.1 Central heating areas

There are seven central heating area provinces and cities: Beijing, Tianjin, Inner Mongolia, Gansu, Ningxia, Shanxi, and Henan. This article assumes the following:

1) Central heating areas do not use electricity for heating;
2) The heating area of central heating areas is based on the heating area data of the relevant statistical yearbooks of various provinces and cities.
3) The central heating area discusses CO2 emission reduction
4) Both regional GDP and total population have been increasing at a constant growth rate.

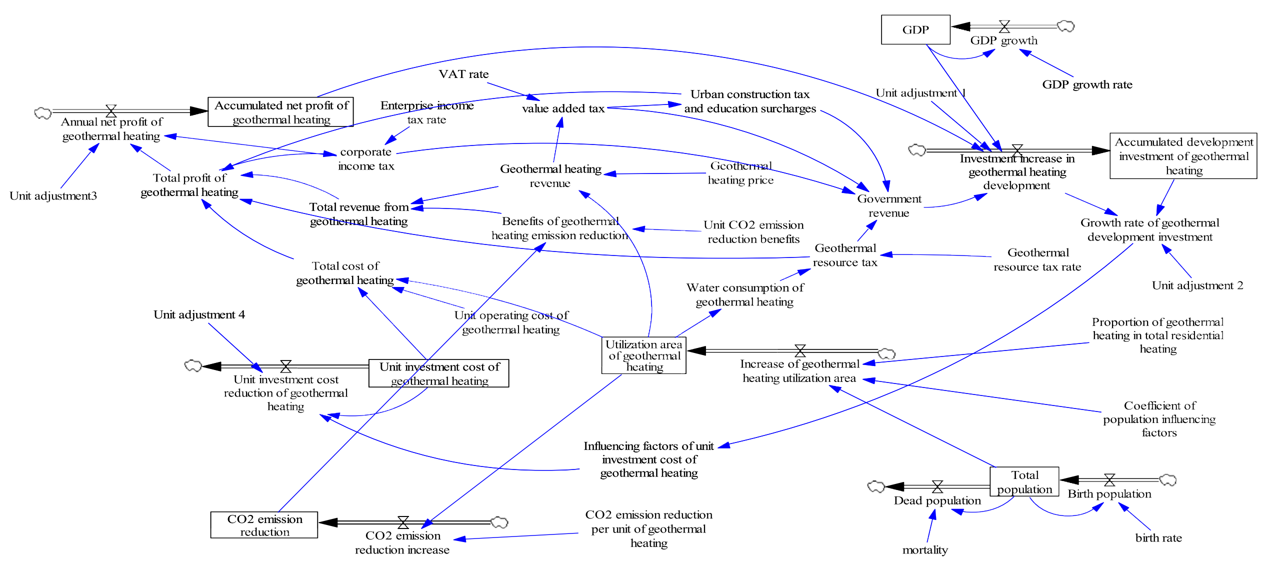

FIGURE 3
Geothermal resource tax system dynamics flow diagram in central heating areas.

5) The initial value of the accumulated net profit of geothermal enterprises is 0 million ¥.

Based on the above research hypotheses, geothermal energy resource tax SD models for central heating areas are constructed. The SD model of the central heating area flow diagrams is shown in Figure 3.

3.3.2 Non-central heating areas

There are 8 non-central heating area provinces and cities: Zhejiang, Jiangsu, Jiangxi, Anhui, Hunan, Chongqing, Guangdong, and Guangxi. This article assumes the following:

1) Residents in non-central heating areas use electricity for self-heating.
2) The heating population in non-central heating areas is fully covered, the heating area is estimated based on the population of each area, and the heating area is estimated based on the population of each region.
3) The non-central heating area discusses CO2 emissions, not CO2 emission reduction.
4) The total population has been increasing at a constant growth rate, and regional GDP has also increased at a certain growth rate.
5) The initial value of the accumulated net profit of geothermal enterprises is 0 million ¥.

Based on the above research hypotheses, geothermal energy resource tax SD models for non-central heating areas are constructed. The SD model of the central heating area flow diagrams is shown in Figure 4.

4 Simulation scenario analysis of geothermal energy resource tax policy

Policy simulation time range: 2021–2035. Step size of simulation empirical analysis: quarter. There were 60 quarters in this study. The economic benefits and environmental benefits of the central heating district and non-central heating district in different scenarios are simulated. The scenarios include the BAU scenario and the non-BAU scenario. BAU scenario: Based on the current resource tax and heating prices of various provinces and cities to simulate and forecast. Non-BAU scenario: Adjust the geothermal resource tax rate and heating price to observe changes in economic benefits and environmental benefits, respectively.

4.1 BAU scenario analysis

4.1.1 Central heating areas

Simulation analysis of geothermal enterprise income and environmental benefits: Beijing, Tianjin, Inner Mongolia, Gansu, Ningxia, Shanxi and Henan central heating districts. In the BAU scenario, the geothermal resource tax rates in the above provinces are 8.5 ¥/m^3, 3 ¥/m^3, 10 ¥/m^3, 3 ¥/m^3, 12 ¥/m^3, 10 ¥/m^3, and 12 ¥/

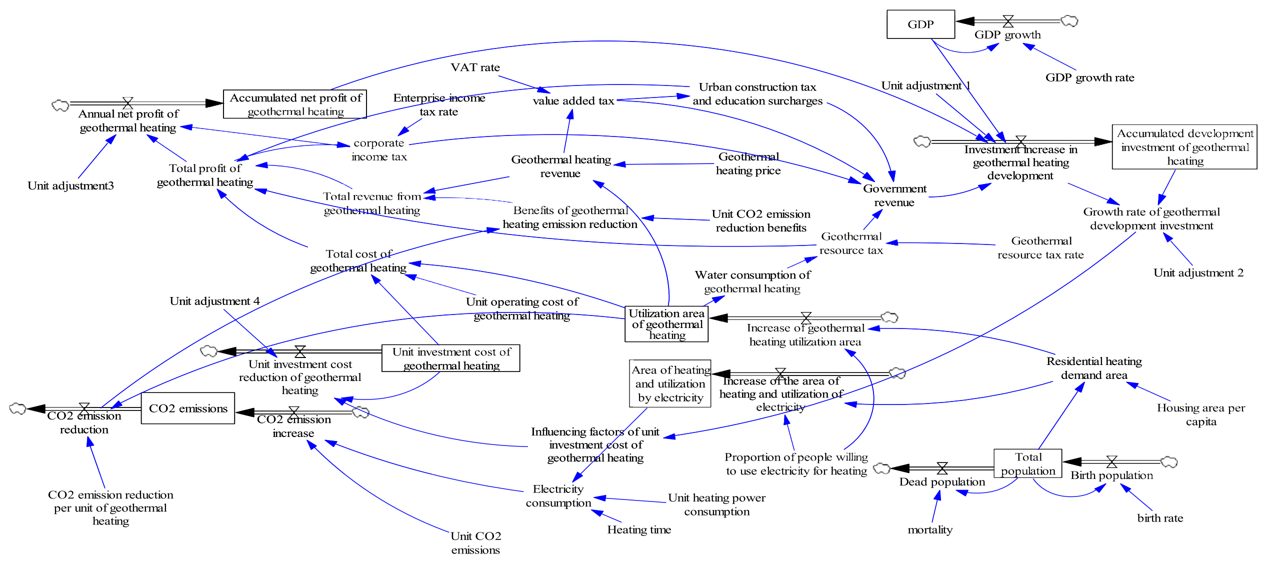

FIGURE 4
The dynamic flow diagram of the geothermal resource tax system in non-central heating areas.

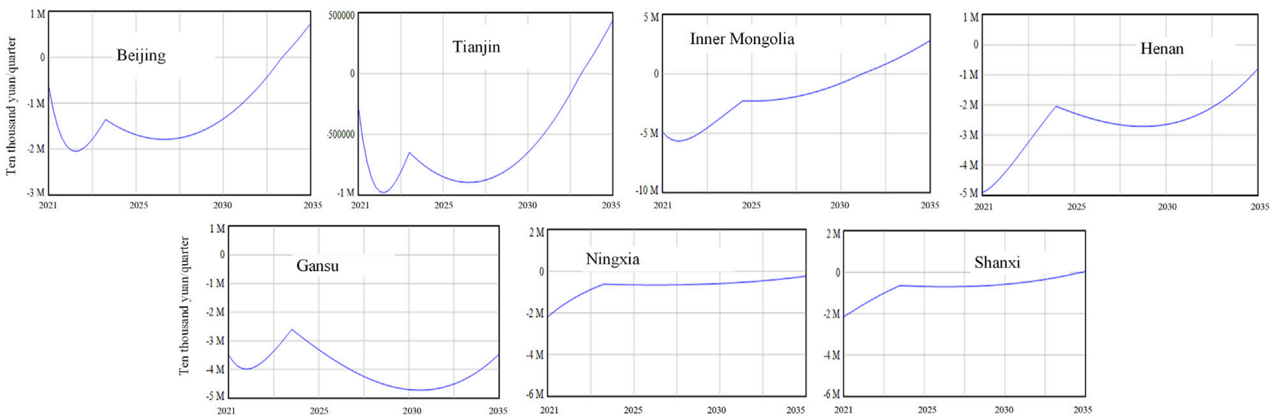

FIGURE 5
BAU scenario of the annual net profit of geothermal heating companies in various provinces and cities in central heating areas.

m^3, and the heating prices are 30 ¥/m^2, 25–40 ¥/m^2, 18.4 ¥/m^2, 7.5 ¥/m^2, 24.5 ¥/m^2, 24 ¥/m^2, and 22.8 ¥/m^2, respectively (Table 2).

1) Profit analysis of geothermal energy enterprises.

According to the current resource tax policies and residential heating prices of all provinces and cities, the annual net profit of geothermal heating enterprises is shown in Figure 5, and the cumulative net profit is shown in Figure 6. In the picture, the abscissa: 2021–2035. Ordinate: annual net profit and cumulative net profit of geothermal heating enterprises (M stands for millions).

The simulation results: 1) under the benchmark scenario, the annual net profit of Beijing, Tianjin, the Inner Mongolia Autonomous Region, and Shanxi Province is greater than zero; Gansu Province, the Ningxia Hui Autonomous Region and Henan Province all have annual net profits less than zero. 2) The inflection point of annual net profit before 2025 is just the time when the unit investment cost of geothermal heating

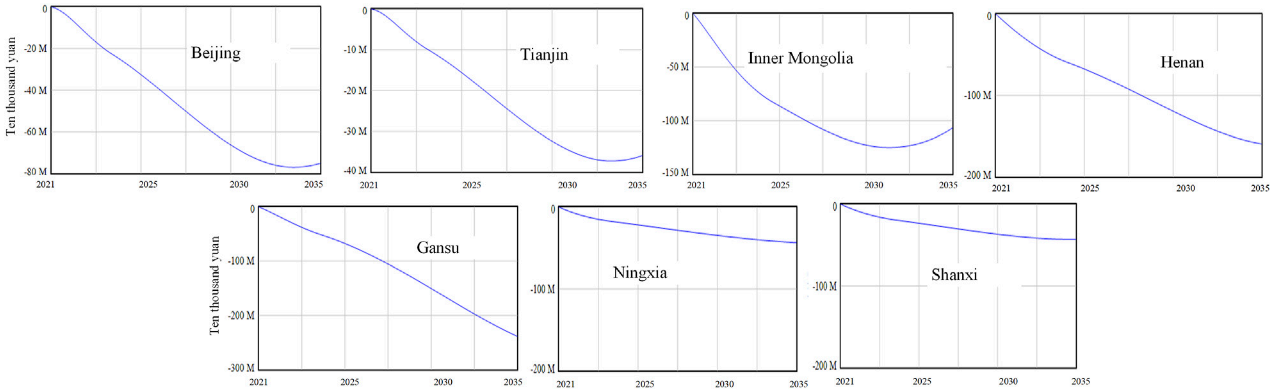

FIGURE 6
BAU scenario of accumulated net profit of geothermal heating enterprises in various provinces and cities in central heating areas.

TABLE 5 Variation range of the unit investment cost of geothermal heating in central heating provinces and cities.

Region	The year when the unit investment cost does not change	Change range of unit investment cost of geothermal heating (¥/m^2)
Beijing	First quarter of 2024	204.9–38.89
Tianjin	Fourth quarter of 2023	204.9–44.19
Inner Mongolia Autonomous Region	Second quarter of 2025	204.9–20.52
Gansu Province	Second quarter of 2024	204.9–34.22
Ningxia Hui Autonomous Region	First quarter of 2024	204.9–38.89
Shanxi Province	Second quarter of 2024	204.9–34.22
Henan Province	Fourth quarter of 2024	204.9–26.50

remains unchanged. Moreover, Table 5 shows that the unit investment cost of geothermal heating stabilized and remained unchanged before 2025. Table 5 shows the change process of the unit investment cost of each province and city in the central heating area. The inflection point in Figure 5 is the point where the unit investment cost begins to remain unchanged. 3) Under the benchmark scenario, the cumulative net profit of these seven provinces and cities is less than zero. The reason is that geothermal heating has a large amount of investment in the early stage, and the annual net profit is relatively late. Therefore, it is difficult to compensate for the cost.

The balance point of the development gains and losses of geothermal refers to the point in time when the annual net profit of geothermal companies is zero. In the central heating area, it is difficult for geothermal companies to generate profits according to the current heating prices and resource tax policies. Table 6 shows the profit and loss balance points of the provinces and cities in the central heating district calculated by simulation. It can be found that Gansu, Ningxia and Henan will not be able to make profits from 2021 to 2035. Therefore, the resource tax rate and price are adjusted, and the profit and loss balance points of the three provinces and cities are calculated.

2) Analysis of CO_2 emissions in central heating areas. In the BAU scenario, geothermal heating accounted for 8%, and the CO_2 emission reduction was calculated after using geothermal heating in the central heating area, as shown in Figure 7. The horizontal axis represents the time from 2021 to 2035, and the vertical axis represents the CO_2 emission reduction. At the same time, M on the vertical axis represents millions, and B represents billions.

The CO_2 emission reductions of the seven provinces and cities in the central heating area exponentially increase, and the CO_2 emission reductions in different regions are different, as shown in Figure 7. By 2035, Gansu Province has the largest CO_2 emission reduction, while Tianjin City has the smallest CO_2 emission reduction. The use of geothermal heating can significantly reduce CO_2 emissions and contribute greatly to global emission reduction and the mitigation of greenhouse

TABLE 6 Heating costs in central heating areas.

Region	The balance point of geothermal geo-development	The profit and loss point after adjusting the resource tax rate or heating price
Beijing	Second quarter of 2034	—
Tianjin	First quarter of 2034	—
Inner Mongolia Autonomous Region	First quarter of 2032	—
Gansu Province	No gains before 2035	When the resource tax is zero, no gains will be made before 2035. Raise the price, get a gain when the price is 20 ¥/m^2, and there will be a profit and loss point 19–20
Ningxia Hui Autonomous Region	No gains before 2035	At the current price, when the resource tax rate is 9 ¥/m^2, the annual net profit will be obtained in 2034. The tax rate is between 9–10, which makes the net profit zero
Shanxi Province	Third quarter of 2035	—
Henan Province	No gains before 2035	Under the current price, when the resource tax rate is 10 ¥/m^2, the annual net profit will be obtained in 2035. The tax rate is between 10–11, which makes the net profit zero

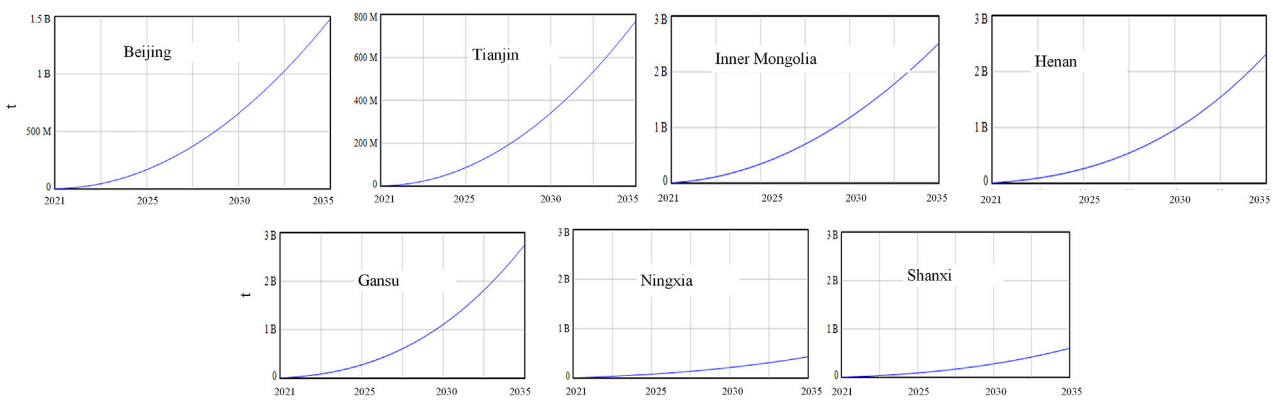

FIGURE 7
BAU scenario of CO_2 emission reduction in central heating provinces and cities.

effects. Geothermal energy can replace coal and natural gas for heating (cooling), bring positive environmental benefits, and significantly affect the mitigation of greenhouse effects.

4.1.2 Non-central heating areas

At present, the policy of non-central heating areas is actively soliciting the public's willingness to install, which has aroused their concern. The research includes the willingness of central heating to install central heating and related charges. The non-central heating areas with geothermal resource taxes are divided into eight regions: Zhejiang Province, Jiangsu Province, Jiangxi Province, Anhui Province, Hunan Province, Chongqing city, Guangdong Province, and the Guangxi Zhuang Autonomous Region. The eight provinces and cities all levy geothermal resource taxes according to water consumption, and all have recharge technology. However, none of them has set a special geothermal resource tax rate for exploiting geothermal resources using recharge technology, and there is no heating price in some areas. In this paper, based on the existing research of non-central heating charging standards, assumptions are made according to the different economic conditions of non-central heating. Assuming that 50% of the population is willing to adopt central heating in non-central heating areas, it can be assumed that 50% of the population currently adopts electric heating.

1) Profit analysis of geothermal energy companies.

The geothermal resource tax rate and geothermal heating price of eight provinces and cities in non-central heating areas are

TABLE 7 Resource tax rates and geothermal heating prices for non-central heating areas.

Region	Resource tax rate (¥/m³)	Heating price (¥/m²)
Zhejiang Province	3	20 (hypothetical value)
Jiangsu Province	10	10
Jiangxi Province	0.6	10 (hypothetical value)
Anhui Province	2	9.5
Hunan Province	3	10 (hypothetical value)
Chongqing city	2	20 (hypothetical value)
Guangdong Province	1	20 (hypothetical value)
Guangxi Zhuang Autonomous Region	4	10 (hypothetical value)

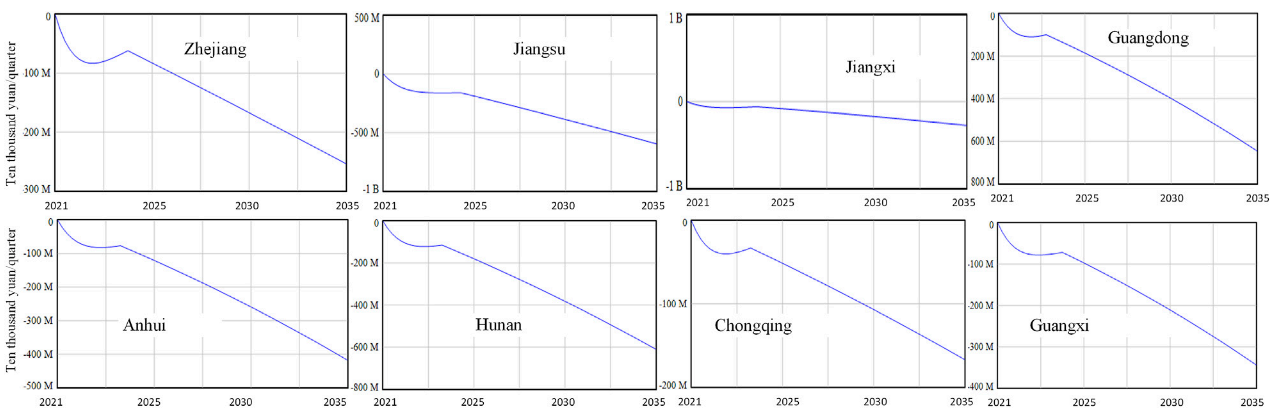

FIGURE 8
BAU scenario of the annual net profit of geothermal heating in non-central heating districts.

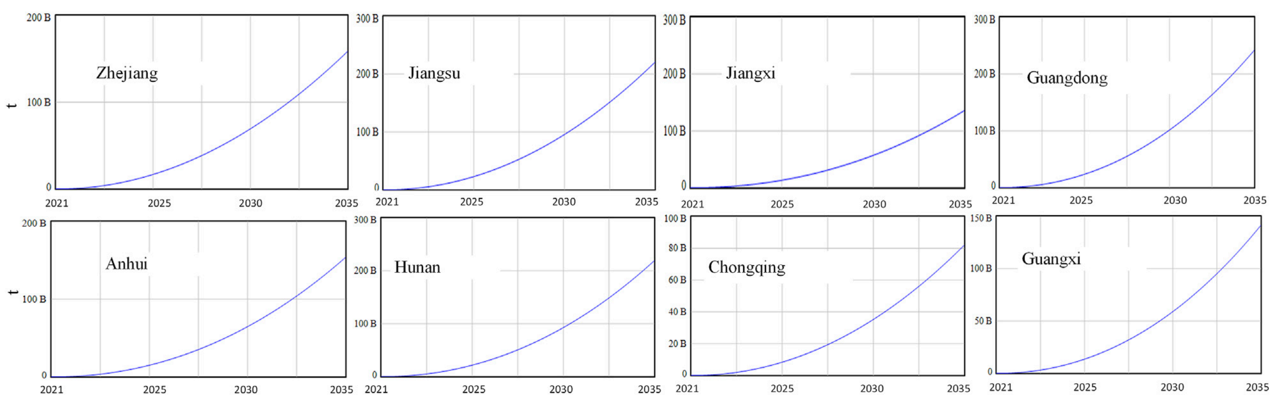

FIGURE 9
BAU scenario of CO_2 emissions of various provinces and cities in non-central heating areas.

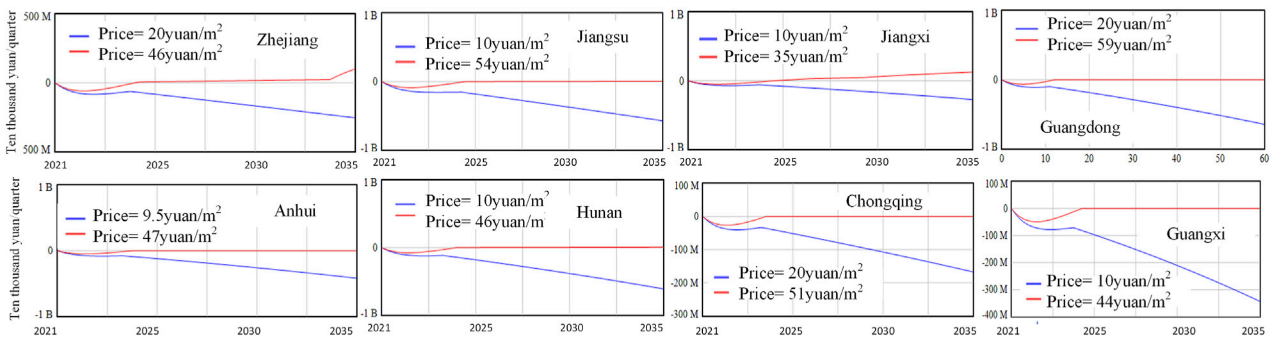

FIGURE 10
Simulation diagram of annual net profit and loss of geothermal heating in non-central heating areas.

shown in Table 7. The data that can be queried in various provinces and cities are copied from Table 3. There are no relevant data on heating prices in Zhejiang Province, Jiangxi Province, Hunan Province, Chongqing City, Guangdong Province, and Guangxi Zhuang Autonomous Region. Therefore, this study sets a hypothetical value of the geothermal heating price according to the economic development of these regions, as shown in Table 7. According to the geothermal resource tax rate and geothermal heating price data, a simulation analysis is carried out for eight provinces and cities with non-central heating, and the results are shown in Figures 8, 9. The horizontal axis represents the time year, from 2021 to 2035, and the vertical axis represents the annual net profit and CO_2 emissions of geothermal heating enterprises. At the same time, M on the vertical axis represents million, and B represents billion.

The simulation results in Figures 8, 9 are as follows: 1) The annual net profit of geothermal enterprises in non-central heating areas is declining. This shows that the current tax rate and heating price of resources are unfavorable to geothermal enterprises and affect the development of geothermal enterprises. 2) The CO_2 emissions of various provinces and cities are different. According to Figure 9, by 2035, Guangdong Province will have the highest CO_2 emissions, and Chongqing will have the lowest CO_2 emissions. The analysis in Table 3 shows that Guangdong Province has the largest population, while Chongqing has the smallest population. Therefore, it is estimated that the CO_2 emissions from each province and city are related to the population.

2) Keep the resource tax rate unchanged, and calculate the price at the breakeven point of the geothermal enterprise

The resource tax rate is a relevant policy that has been promulgated by various provinces and cities. This subsection, based on the current resource tax rate, studies the adjustment of geothermal heating prices under the condition that the resource tax rate remains unchanged and observes the time when the annual net profit of geothermal enterprises in each province and city is obtained. The simulation results are shown in Figure 10. The horizontal axis represents time from 2021 to 2035, and the vertical axis represents the annual net profit of geothermal heating enterprises. At the same time, M on the vertical axis represents million, and B represents billion. The assumptions are as follows: the heating price in the BAU scenario in Zhejiang Province is 20 ¥/m²; the heating price in the BAU scenario in Jiangsu Province is 10 ¥/m²; the heating price in the BAU scenario in Jiangxi Province is 10 ¥/m²; the heating price in the BAU scenario in Anhui Province is 9.5 ¥/m²; the price of geothermal heating in Hunan Province is 10 ¥/m²; the benchmark price of geothermal heating in Chongqing is 20 ¥/m²; the price of geothermal heating in Guangdong is 20 ¥/m²; and the price of geothermal heating in Guangxi Zhuang Autonomous Region is 10 ¥/m². The price of geothermal heating is then gradually adjusted to find the balance point of profit and loss.

All provinces and cities in non-central heating zones can obtain annual net profit by adjusting geothermal heating prices, as shown in Figure 10. When the price of non-central heating in 8 provinces and cities ranges from 35 ¥/m² to 59 ¥/m², the net profit of geothermal heating enterprises will be greater than zero in the fourth quarter of 2023 and the second quarter of 2025, as shown in Table 8. It can be seen that the use price of geothermal heating in various provinces and cities in non-central heating areas is generally higher.

4.2 Non-BAU scenario analysis

4.2.1 Reanalysis of geothermal energy utilization possibility in gansu province, ningxia hui autonomous region and henan province

The calculation under the BAU scenario shows that Gansu Province, Ningxia Hui Autonomous Region, and Henan Province cannot obtain net profit before 2035. Assuming that

TABLE 8 Collection of geothermal resource taxes in 8 provinces and cities for non-central heating.

Region	Assumed geothermal heating usage price (¥/m²)	The starting point where the company's net profit is greater than zero
Zhejiang Province	46	The fourth quarter of 2024
Jiangsu Province	54	The second quarter of 2025
Jiangxi Province	35	The second quarter of 2025
Anhui Province	47	The third quarter of 2024
Hunan Province	46	The fourth quarter of 2024
Chongqing city	51	The second quarter of 2024
Guangdong Province	59	The fourth quarter of 2023
Guangxi Zhuang Autonomous Region	44	The fourth quarter of 2023

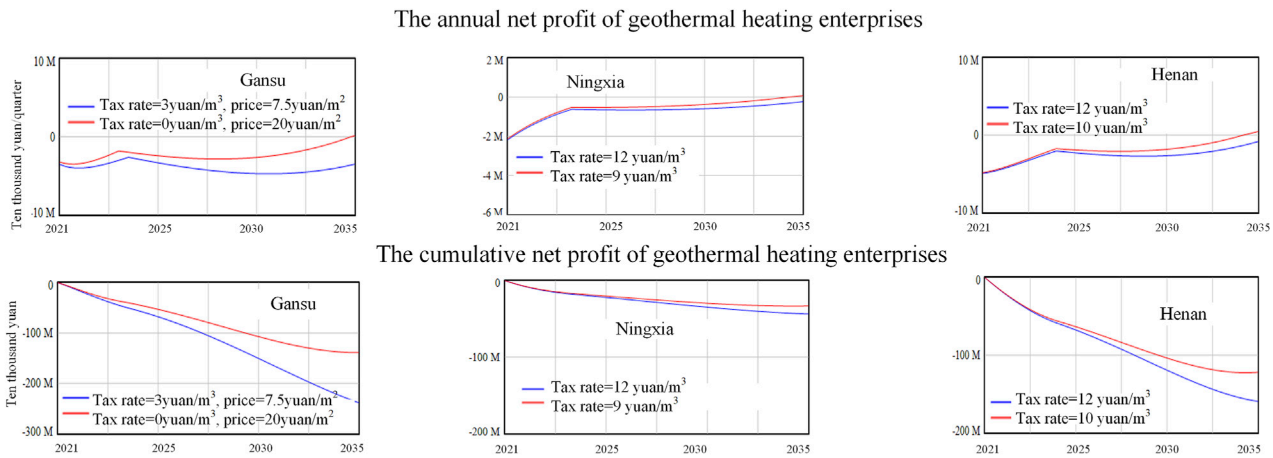

FIGURE 11
Forecast of annual net profit and accumulated net profit in Gansu Province, Ningxia Hui Autonomous Region and Henan Province.

these three regions can obtain annual net profits before 2035, the geothermal resource tax rate or geothermal heating price is simulated, among which the geothermal resource tax rate in Gansu Province is adjusted from 3 ¥/m^3 to 0 ¥/m^3, and the heating use price is 20 ¥/m^2; the geothermal resource tax rate of the Ningxia Hui Autonomous Region is adjusted to 12 ¥/m^3 to 9 ¥/m^3, and the heating price is 24.5 ¥/m^2; the resource tax rate of Henan Province is 12 ¥/m^3 to 10 ¥/m^3; and the heating price is 22.8 ¥/m^2. The results are shown in Figure 11.

The simulation results: 1) Gansu Province is the province where the annual net profit of enterprises will be greater than zero before 2035 by adjusting both the resource tax rate and price. If the resource tax rate of Gansu Province is adjusted to 0 ¥/m^3 and the geothermal heating price is 20 ¥/m^2, the annual net profit can be obtained in 2035, and the profit and loss point is between 19–20 ¥/m^2. This is because the resource tax rate and heating price under the BAU scenario in Gansu Province are relatively low, and it is difficult for geothermal enterprises to make profits. 2) Ningxia Hui Autonomous Region and Henan Province are the provinces where keeping the price unchanged and only adjusting the resource tax rate can make the annual net profit of enterprises greater than zero before 2035. When the geothermal heating price of the Ningxia Hui Autonomous Region remains unchanged at 24.5 ¥/m^2, the annual net profit can be obtained by adjusting the resource tax rate to 9 m^3 in 2034, and the profit and loss point appears at the geothermal resource tax rate of 9–10 ¥/m^3. In Henan Province, when the geothermal heating price remains unchanged at 22.8 ¥/m^2, the resource tax rate is adjusted to 10 ¥/m^3, and the annual net profit can be obtained in 2035.

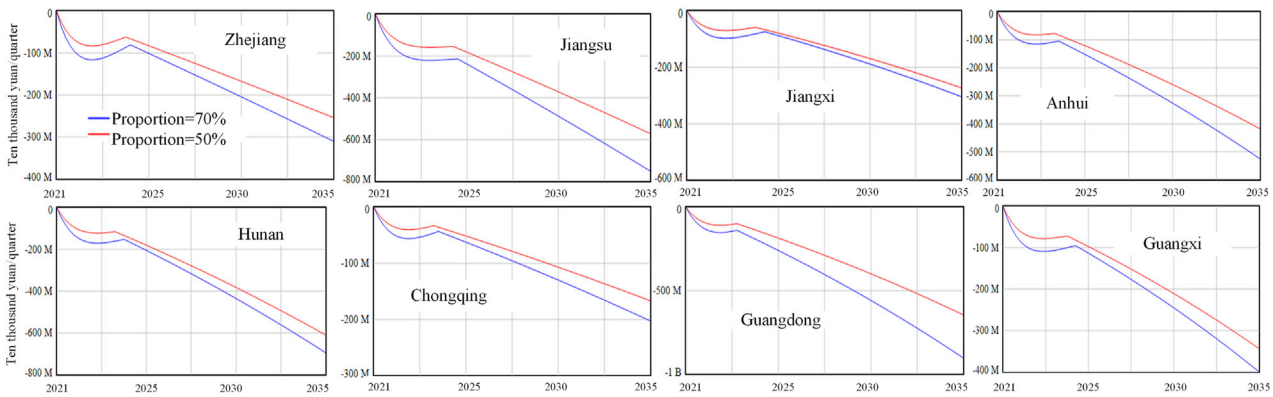

FIGURE 12
Annual net profit of non-central heating provinces and cities after adjusting heating proportions.

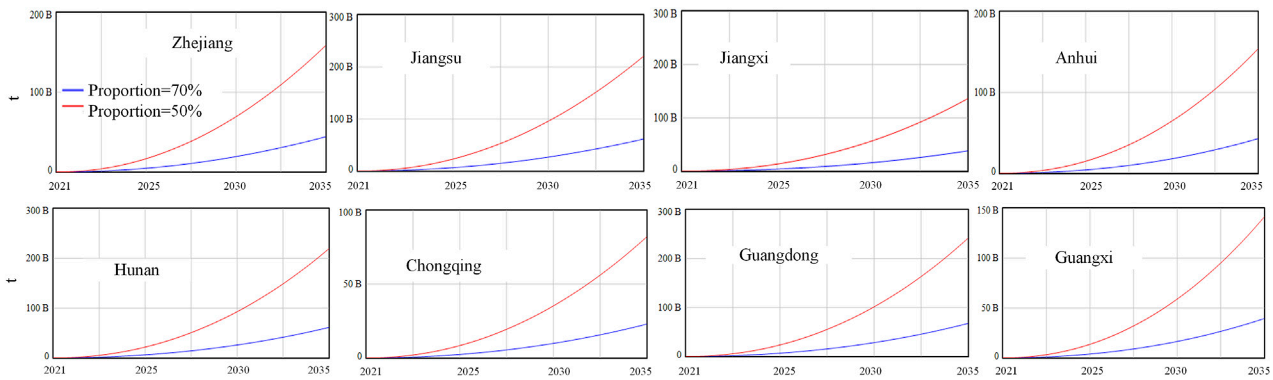

FIGURE 13
CO_2 emissions of non-central heating provinces and cities after adjusting heating proportions.

The profit and loss point appears in the geothermal resource tax rate of 10–11 ¥/m^3. The heating prices in these two areas are relatively high, but the resource tax rate is also relatively large; finally, there is no profit or loss point under the BAU scenario.

4.2.2 Environmental benefit analysis of non-central heating areas under geothermal energy utilization

In this paper, it is assumed that the 8 non-central heating areas of Zhejiang, Jiangsu, Jiangxi, Anhui, Hunan, Chongqing, Guangdong, and Guangxi adjust the proportion of electricity heating to 30%, that is, increase the proportion of geothermal heating to 70%. Compared with the BAU scenario, the simulation results are shown in Figure 12. Figure 13 CO_2 emission reductions in non-central heating provinces and cities are shown in Table 9. The horizontal axis represents time from 2021 to 2035, and the vertical axis represents the annual net profit and CO_2 emissions of geothermal heating enterprises. At the same time, M on the vertical axis represents million, and B represents billion.

The simulation results: 1) after increasing the proportion of geothermal heating, the annual net profit and cumulative net profit of geothermal heating enterprises in eight provinces and cities have been reduced. This is because geothermal enterprises are already in a loss state. The more people use them, the more losses there will be, the lower the annual net profit compared with the BAU scenario, and all of these are in a state of increasing losses. 2) When the proportion of geothermal heating is increased to 70%, the CO_2 emissions of non-central heating provinces and cities are significantly reduced, which indicates that increasing the proportion of geothermal

TABLE 9 CO_2 emission reduction after increasing the proportion of geothermal heating in non-central heating provinces and cities.

Region	CO_2 emission reduction by 2035 (million tons)
Zhejiang Province	114,455
Jiangsu Province	159,108
Jiangxi Province	98,047.5
Anhui Province	110,913
Hunan Province	158,104
Chongqing city	59,174
Guangdong Province	174,511
Guangxi Zhuang Autonomous Region	101,928

heating can reduce CO_2 emissions. Guangdong Province has the largest CO_2 emission reduction of 174,511 million tons. Chongqing has the lowest CO_2 emission reduction of 59,174 million tons. Through the comparison of data, the CO_2 emission reduction is related to the population number of provinces and cities. The greater the population is, the greater the CO_2 emission reduction.

4.3 Results discussion

4.3.1 Economic benefit analysis

1) According to the current heating price and resource tax policy, it is difficult for geothermal enterprises to obtain benefits.

From the perspective of annual net profit, in the BAU scenario, the annual net profit of central heating districts in Beijing, Tianjin, Inner Mongolia and Shanxi will be greater than zero from 2034. Gansu, Ningxia and Henan will not reap benefits in 2021–2035. By adjusting the resource tax rates and prices of Gansu, Ningxia and Henan, it can be concluded that Gansu Province will gain profits in 2035 when the resource tax remains unchanged and the price is 20 ¥. When the price remains unchanged and the resource tax rate is 9 ¥/m^3, Ningxia will obtain annual net profit in 2034. Henan will make an annual net profit in 2035 when the price stays the same and the resource tax rate is 10 ¥/m^3. Therefore, provinces and cities need to determine appropriate resource tax rates and prices based on the needs of local enterprises. In the non-central heating area, the annual net profit of geothermal enterprises in all provinces and cities under the BAU scenario is less than zero, and it is on a downwards trend. From the perspective of cumulative net profits, geothermal enterprises in all provinces and cities have achieved cumulative net profits less than zero regardless of the baseline scenario or after adjusting the resource tax rate or heating price.

In conclusion, the existing resource tax rate and heating price in non-central heating areas are not conducive to the development of geothermal enterprises. Keeping the resource tax rate unchanged and adjusting the price of geothermal heating, it can be concluded that the geothermal price is relatively high in provinces and cities in the non-central heating area. When the price is 35–59 ¥/m^2, the enterprise can make a net profit in approximately 2024. At the same time, the investment in geothermal heating is large in the early stage, and the annual net profit is obtained relatively late; it is difficult to recover the cost.

2) When the utilization ratio increases, more initial investment is needed, and the time to obtain income is prolonged. Therefore, in the early stage of development, economic benefits may not be ideal.

4.3.2 Environmental benefit analysis

This study mainly analyses the environmental benefits of geothermal heating under different resource tax policies from the perspective of carbon emissions. The simulation results show that by 2035, in central heating areas, Gansu Province will have the largest carbon emission reduction, while Tianjin will have the smallest carbon emission reduction. For non-central heating areas, Guangdong Province will have the largest carbon emission reduction of 174.511 billion tons. Chongqing municipality will have the lowest carbon reduction of 59.174 billion tons. As the proportion of geothermal heating increases, carbon emissions decrease significantly, and CO_2 emissions are different in different regions. The results show that both carbon emission and carbon emission reduction are affected by regional population.

Therefore, the use of geothermal resources can effectively reduce carbon emissions. The exponential growth trend of carbon emission reduction shows that the use of geothermal resources has a positive effect on mitigating the greenhouse effect and reducing greenhouse gas emissions.

5 Conclusion and policy implications

Conclusion: Increasing the utilization ratio of geothermal heating can improve the environmental benefits. The setting of the resource tax rate and heating price should consider both the benefits of enterprises and the needs of residents, which can maintain the balance of the geothermal heating market, improve the efficiency of resource utilization, and promote the construction of an ecological civilization. The policy recommendations are as follows: 1) For the government, geothermal heating price subsidies should be combined with local geothermal enterprises, economic conditions and residents' willingness to pay for heating. The demand of geothermal enterprises and residents should be met simultaneously.

Taking Beijing as a reference, the heating price subsidy is 30–50 ¥/m^2. 2) Geothermal enterprises can obtain carbon emission reduction benefits through carbon trading. At the same time, the use of recharge technology is promoted to realize the recycling of resources and protect geothermal resources. 3) For residents, it is necessary to formulate reasonable promotion policies in combination with residents' heating demand and willingness to pay. Such as the establishment of reasonable heating prices.

With the deterioration of the global environment and the shortage of resources, geothermal energy as a clean and renewable energy source for clean heating (cooling) meets the requirements of high-quality national economic development. It also has important prospects for the improvement of the environment. The policy evaluation of the geothermal resource tax rate and heating price in this paper is helpful to determine the direction of resource tax reform in the next stage. This means that it can provide a reference for the rationality of resource taxes in geothermal energy heating processes. Through formulating reasonable policies, enterprises can be guided to increase investment in technology R&D to achieve green development and safe production. At the same time, it can promote the formation of a green lifestyle and improve people's quality of life. It can also promote the rational use of energy, promote ecological environmental protection, and promote the construction of an ecological civilization system. During the research, it is found that only a few areas have adopted recharge technology, and the rational application and promotion of recharge technology and the rationality of charging the geothermal energy resource tax according to water resources still need to be further discussed.

Author contributions

Yy: Methodology, Software, Writing–original draft. ZJ: Data curation, Formal analysis, Writing. HY: Investigation, Resources. KX: Writing–review & editing.

Funding

Supported by the Key Project of Beijing Social Science Foundation (19YJA001); the Fundamental Research Funds for the Central Universities (2021SKGL01; 2022YJSGL05).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 25 October 2022
DOI 10.3389/fenvs.2022.1036810

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OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Environmental Economics and Management, a section of the journal Frontiers in Environmental Science

RECEIVED 05 September 2022
ACCEPTED 11 October 2022
PUBLISHED 25 October 2022

CITATION
Zhang C, Zou CF, Luo W and Liao L (2022), Effect of environmental tax reform on corporate green technology innovation.
Front. Environ. Sci. 10:1036810.
doi: 10.3389/fenvs.2022.1036810

Effect of environmental tax reform on corporate green technology innovation

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China has recently taken several measures to counter the environmental pollution caused by the crude model of past economic development. Among them, taxation has proved especially efficient. We take the Environmental Protection Tax Law, implemented on 1 January 2018, as a quasi-natural experiment to study the effect of environmental protection tax reform on corporate green technology innovation. We analyze data on Shanghai and Shenzhen A-share listed companies for 2013–2020. We find that raising the tax levy significantly promotes green innovation among enterprises. The promotion effect is more significant in state-owned enterprises, heavily polluting enterprises, and the eastern region. The findings of the full sample and subsample still hold after replacing the explanatory variables for stability testing. The effects vary significantly based on property rights, geography, and level of industry pollution. Nevertheless, environmental tax reform is an effective initiative toward environmental protection, even if the complexity of China's economic environment reveals some variation in the effects of this policy reform. We make suggestions to address these differences for future studies.

KEYWORDS

environmental tax, environmental tax reform, environmental pollution, green technology innovation, double difference

Introduction

China still faces grave environmental concerns resulting from rapid industrialization, urbanization and development, particularly the pollution of its air, water, and soils (Sun et al., 2018). The maturation of industrialization and the information society brought China's attention to "green production" and "green innovation," already popular trends in Western markets and economies. The report of the 19th National Congress also envisions a new era of "socialism with Chinese characteristics." It recognizes a change in the contradictions of society and how unbalanced, insufficient development is throttling balanced growth.

The Chinese economy entered a new normal to achieve high-quality development. The evolution means increasing and stricter environmental protection requirements, ushering the need for corporate technological innovation spanning production to operation. Enterprises must eliminate backward production capacity, promote transformation and upgrades, and reduce at source the generation and emission of pollutants. This new era also requires the government to raise its emission standards for enterprise-generated pollutants, and accordingly, implement a stricter regulatory system.

The pollution caused by enterprises' production and operation has negative externalities. To reign in these externalities, the government must enforce macro control and solve market failure through taxation, a most direct and efficient solution. This measure may inspire independent R&D and green innovation among enterprises seeking to "green" their production and operations, reduce environmental pollution at source, and contribute to environmental protection.

The first of its kind in the country, the Environmental Protection Tax Law of the People's Republic of China (hereafter, "the Law") came into effect on 1 January 2018. Its fundamental purpose is to protect the environment, reduce pollutants, and actively promote an *ecological civilization*. More specifically, it shifted emission regulations from under administrative fee management to the Law, marking a paradigmatic shift in how the government approaches environmental protection. The Law embodies the legal and economic instruments of environmental protection and aims to push enterprises toward green technology innovation. In this context, we examine the effect of the Environmental Protection Tax Law reform (hereafter, "tax reform") on green technology innovation in enterprises.

We consider this Law a quasi-natural experiment to transition from emission charges to environmental protection tax. Based on emission charges, the new tax impacts the tax burden in two ways: the levy standard remains the same after the reform in some provinces, while it increases after the reform in other provinces. In this study, we take enterprises that fall under tax burden leveling as the control group and those under the tax burden increase as the experimental group. We aim to determine whether the effect of tax leveling and tax increases facilitate or inhibit green technology innovation in enterprises. To that end, we investigate the heterogenous effects of tax reform on green technology innovation (hereafter, green innovation) in terms of property rights, the region where the enterprise is located, and the degree of pollution in the industry.

We believe that our study has important marginal contributions. First, despite the recency of the Law's implementation (year 2018), scholars seldom examined the reform with rigor, especially its effect on enterprises' green innovation. Our should be a useful reference for further development of subsequent environmental protection taxes. Second, we select intuitive indicators of green innovation output. Specifically, two indicators prove helpful in our empirical analysis: the number of green patent applications and the number of more innovative green invention patent applications. Third, our choice of a quasi-natural experiment with the tax reform and the difference-in-differences (DID) method, excluding other interfering factors, successfully tests the net effect of the tax reform on green innovation. The findings provide support for the effect of the tax reform on green innovation.

Literature review

In order to achieve the UN SDGs by 2030, sustainable development and ecological civilisation are essential. The integration of science and policy is of vital importance (Bryan et al., 2018). China's 2018 tax reform is a special kind of environmental regulation that warrants rigorous study of its effect on green innovation. The Porter hypothesis—that environmental regulation stimulates corporate green innovation—is a popular subject of investigation. Most studies conform to three dominant views. First, environmental regulation has an innovation compensation effect. A well-designed environmental regulation policy will promote green innovation among enterprises. Macro- and micro-level studies on the Porter hypothesis support the "innovation compensation" effect. For example, Wang and Zhang (2020), Yuan and Che (2019), and Wang and Chen (2018) confirm the Porter hypothesis using empirical data for different dimensions (e.g., company size, environmental regulations, board governance) and industries. Xiong et al. (2020) and Wang et al. (2021a) use the comprehensive environmental regulation policy of a low-carbon city pilot implemented by the Chinese central government in 2010 as a quasi-natural experiment to examine its effects on firms' green innovation and green total factor productivity by applying the double- and triple-difference methods, respectively. Xiong et al. (2020) find that the pilot policy significantly improved green innovation to a certain extent, Wang et al. (2021a) conclude that the policy could directly promote green total factor productivity at the city level. Yi et al. (2021) used a multi-period DID model to conduct a quasi-natural experiment on the environmental governance mechanism of the first round of the Central Environmental Protection Inspectorate. They show that the innovation compensation effect was greater than the cost-following effect, which improved green innovation.

Second, environmental regulation has a "cost-following" effect: environmental regulation inhibits green innovation. In their study of China's SO_2 emissions trading scheme pilots, Tu and Chen (2015) argue that the Porter effect did not appear significantly at this stage. They attributed this result to the overall weak environmental regulation and market inefficiency. Jia and Cui (2020) found that market-based and voluntary environmental policy instruments have not played an effective role in green innovation. Zhong and Shang (2022) analyze the mechanism and effect of environmental regulation on the efficiency of urban industry. Guan et al. (2022) conduct an empirical test based on common Frontier robust productivity to examine the impact of environmental regulations on urban green productivity from a spatial spillover perspective.

Third, environmental regulation has an uncertain effect on green innovation; that is, the relationship is non-linear. Zhang et al. (2019) and Du et al. (2019) find that the effect of environmental regulation on the output of green innovation and industrial green competitiveness in micro-analysis had a U-shaped relationship, further verifying the validity of Porter's hypothesis. Dong and Wang (2021) discover that city-level environmental regulation had obvious threshold characteristics, in which the regulation first depressed progress before improving it. Tao et al. (2021)measure green technology innovation at the quantitative and qualitative levels of green patents. They also measure the quantity and quality of innovation by the higher number of green patent applications and constructing a patent knowledge breadth indicator, respectively. Wang et al. (2021b) used green patent data of Chinese A-share listed companies from 2004 to 2015 to show that, at the early stages under weak environmental regulation, increasing its intensity prompted enterprises to increase pollution control investment. This reduced R&D and innovation investment, leading to lower green innovation capacity. At a certain level of regulation, however, enterprises increased green innovation inputs to improve the input–output efficiency, indicating a U-shaped. This non-linear relationship between regulation and innovation was further studied. The authors apply a double-difference method to examine the effect of the environmental target responsibility system on the quantity and quality of green innovation and find an increase in innovation quantity, but a decline in its quality.

In summary, the literature finds a promotion, an inhibition, and an non-linear effect of regulation on green innovation, possibly because the policies under examination have more indirect effects on firms. However, China is a government-oriented emerging market, and its firms may take taxes, as a special type of environmental regulation that directly affects their tax revenues, more seriously.

Research hypotheses

Tax reform and level of green innovation

Two main changes characterize the collection and management of environmental protection tax. First, the tax and environmental protection departments coordinate to collect and manage taxes, where the former discharges these duties in accordance with the taxation law and the latter monitors and manages the emission of pollutants. The two departments coordinate through an information-sharing platform to regularly deliver relevant data. Second, taxpayers are divided into key and non-key monitored taxpayers for classification and management (Wen, 2015). These changes elevate taxation from the administrative fee level to the legal level, imbuing the Law with tax rigidity and legal authority. The tax levied is earmarked for specific use, which systematically reduces the possibility of enterprises evading environmental governance through rent-seeking (Jin et al., 2020).

The fundamental purpose of continuously increasing the standard of environmental taxes and fees, implementing a stricter collection and management system, and earmarking management for pollution prevention and treatment is to force enterprises to undergo "green upgrading." This would reduce pollutants at their source to address the symptoms and root causes of environmental pollution. In the long run, these penalties pressure enterprises to actively save energy, reduce emissions, optimize their economic structure, and make green products to obtain sustainable profit points (Albrizio et al., 2017). The Porter hypothesis is thus expected to achieve industry-wide and systemic economic development. This process of transformation has long been a subject of intense scientific scrutiny. Li and Xiao (2020), for example, find that the push-back effect of emission charges on green innovation were reflected in both external pressure and internal incentives. Similarly, Wen and Zhong (2020) consider the increase in environmental tax levy in 2007 as an exogenous event. Their quasi-natural experiment reveals that the adjustment of the emission charge levy significantly benefited the extensive and intensive margins of green innovation, supporting the Porter hypothesis. In contrast, Wen and Zhou (2019) argue that the differential emission fee levy standards were more conducive to the development of a green economy. Zhao et al. (2016) reveal that under the combined effect of market, product, and environmental taxes, a higher environmental tax promoted environmental technology innovation, while a lower overall tax was not conducive to technology innovation. We thus propose the first hypothesis.

H1. The shift from sewage charges to environmental taxes has a promotion effect on the level of green innovation among enterprises.

Property rights

The effect of the tax reform on green innovation may vary according to the enterprises' property rights. First, China's special market economy system is characterized by fundamental differences between state-owned enterprises (SOEs) and non-SOEs in terms of property rights. Hence, each type of enterprise also differs in investment, management, and productivity. Tong et al. (2014) best define these idiosyncrasies in their study, showing that while the Chinese government encouraged SOEs to apply for patents after the second revision of the patent law, invention patents did not increase significantly, even as the total number of patents

TABLE 1 Comparison of emission fees and 2018 environmental protection tax levy standards by province.

Province	Atmospheric pollutants		Water pollutants	
	Sewage charges	Environmental protection tax	Sewage charges	Environmental protection tax
Beijing	10	12	10 (12)	14
Tianjin	6.3 (8.5)	10	7.5 (9.5)	12
Hebei	2.4	First-class major pollutants 9.8, other 4.8; second-class major pollutants 6, other 4.8; third-class pollutants 4.8	2.8	First-rate major pollutant 11.2, other 5.6; second-rate major pollutant 7, other 5.6; third-rate pollutant 5.6
Shanghai	4	6.65 (7.6)	3	5 (4.8)
Shandong	6 (Other 1.2)	6 (Other 1.2)	1.4 (Other 0.9)	3 (Other 1.4)
Jiangsu	3.6	Nanjing 8.4, Wuxi, Changzhou, Suzhou, Zhenjiang 6, others 4.8	4.2	Nanjing 8.4, Wuxi, Changzhou, Suzhou, Zhenjiang 7, others 5.6
Zhejiang	1.2	1.8 (other 1.2)	1.4	1.8 (other 1.4)
Chongqing	1.2	2.4	1.4	3
Sichuan	1.2	3.9	1.4	2.8
Shanxi	1.2	1.8	1.4	2.1
Hunan	1.2	2.4	1.4	3
Fujian	1.2	1.2	1.4	1.5 (other 1.4)
Henan	1.2	4.8	1.4	5.6
Hubei	2.4	2.4 (Other 1.2)	2.8	2.8 (other 1.4)
Yunnan	1.2	1.2 in 2018, 2.8 in 2019	1.4	1.4 in 2018, 3.5 in 2019
Guizhou, Hainan	1.2	2.4	1.4	2.8
Guangdong, Guangxi	1.2	1.8	1.4	2.8
Tibet	0.6	1.2	0.7	1.4
Heilongjiang	1.2	1.2	1.4	1.4
Inner Mongolia	1.2	1.2 in 2018, 1.8 in 2019, 2.4 in 2020	1.4	1.4 in 2018, 2.1 in 2019, 2.8 in 2020
Anhui	1.2	1.2	1.4	1.4
Liaoning, Jilin, Jiangxi, Gansu, Qinghai, Shaanxi, Ningxia, Xinjiang	1.2	1.2	1.4	1.4

Note: 1. Air pollutants are mainly sulfur dioxide and nitrogen oxides; water pollutants are mainly chemical oxygen demand and ammonia nitrogen. Some provinces have different levy standards for the two pollutants. The former number is for sulfur dioxide and chemical oxygen demand for air pollutants and water pollutants, respectively, and the latter for nitrogen and ammonia nitrogen, respectively; other denotes other pollutants.

did. These results effectively imply that the SOEs' innovation strategies are more likely to be weighted to meet the requirements of national policies than to reflect quality.

Second, SOEs, being national property in nature, usually have stronger bargaining power in negotiations with local governments; they are more likely to receive implicit preferences in the implementation of environmental policies (Jin et al., 2020). SOEs' policy preferences are often protected by strong administrative barriers, and a substitution effect that weakens their incentive to innovate compared with non-SOEs (Kou and Liu, 2020). In contrast, the market-oriented private enterprises have a stronger incentive to innovate than SOEs (Kou and Liu, 2020). Market-oriented private enterprises must stimulate internal green innovation to achieve sustainable development in the face of environmental regulations, while also reducing their operating costs. However, as SOEs benefit from "state backing," they also

TABLE 2 Definition of main variables.

Variable type	Variable name	Symbols	Definition
Explained variables	Green Patent	lnGreia	The total number of green patents independently applied for by the enterprise in the year plus one, and taken as the logarithm
	Green Invention Patent	lnGreInvia	The total number of green invention patents independently applied for by the enterprise in the year plus one, and taken as a logarithm
Explanatory variables	Policy dummy variables	Tax	If the enterprise is located in a province with a higher environmental tax standard, take 1; otherwise take 0
	Time dummy variables	Time	The value is 1 for 2018 and beyond; otherwise it is 0
	Net policy effect	Time*tax	Product of the dummy variables time and tax
Control variables	Age of listing	Age	Year of observation minus year of company listing
	Capital Intensity	cap_inten	Assets at the end of the year divided by operating income for the year
	Shareholding ratio of top ten shareholders	top10	Number of shares held by the top ten shareholders divided by the total number of shares
	Tobin Q	tobinq	Ratio of market value to book value
	Percentage of independent directors	independ	Number of independent directors as a percentage of the number of board of directors
	Gearing ratio	Lev	Total liabilities as a percentage of total assets
	Degree of separation of powers	Sep	Percentage of ownership of the first shareholder/percentage of control of the first shareholder
	Industry Structure	GDP_3	Tertiary sector as a percentage of GDP
	Environmental Regulation	fiscal	Local environmental protection expenditure as a percentage of GDP
	Gearing ratio	TDR	Total liabilities as a percentage of total assets
	Environmental pollution intensity	lnSO2	Logarithm of sulfur dioxide emissions
	Foreign Trade	IEtrade	Logarithm of total regional foreign trade

benefit in resource allocation, especially financial support (Zeng, 2021). Thus, we propose the second hypothesis.

H2. The policy shift from emission to environmental protection tax has a more significant effect on promoting green innovation in non-SOEs than in SOEs.

Regional heterogeneity

We expect regional heterogeneity in the effect of the tax reform on green innovation. China is spread over a vast geographic area, leading to diverse regional economic characteristics and stark variations in industrial development. For example, because of the relatively slow growth in Western China, some policies encourage an influx of capital and technology to support development in the region (Wu and Li, 2009). In contrast, East China is abundant in capital and technology resources, and can respond to the tax reform by carrying out green innovation.

Yet, when the Law was implemented in 2018, most of the central and western provinces did not actually raise the environment tax rate, despite a unified implementation of the Law. This was primarily because each province sets its own environment tax rate, and the provinces that implemented the Law were mainly the central and western provinces. We thus propose our third hypothesis.

H3. The policy reform of changing emission fees to environmental protection tax has a more significant

TABLE 3 Double-difference model and parameter definitions.

	Collection of sewage charges (time = 0)	Imposition of environmental protection tax (time = 1)	Differential
Control group: Tax burden leveled (tax = 0)	β0	β0+β1	β1
Experimental group: tax burden increased (tax = 1)	β0+β2	β0+β1+β2+β3	β1+β3
Differential	β2	β2+β3	β3

role in promoting green innovation for enterprises in the eastern region than in the central and western regions of China.

Heterogeneity in enterprise characteristics

Pollution levels in different industries also determine the effect of the tax reform on green innovation. Each industry has its own process and product characteristics, which leads to varying degrees of polluting emissions. Without green innovation and upgrade of processes/products, the environmental tax burden will be much higher on heavily polluting enterprises than on less- and non-polluting enterprises.

However, China's vision of an ecological civilization requires that heavy polluters invest in green innovation, or otherwise face burdensome environmental protection costs or decreased development prospects due to their long-term, pollution-heavy, unsustainable development models. On this point, Tang et al. (2013) argue that heavily polluting industries have greater environmental investments than industries that pollute less. Similarly, Jia and Cui (2020) argue that low-carbon city pilot policies promote more significant green innovation in high-carbon industries than in low-carbon industries. They further suggest that this industry heterogeneity is primarily why the effect of policy on green innovation is limited overall. We thus propose our final hypothesis.

H4. The policy reform of changing emission fees to environmental protection taxes has a more significant effect on promoting green innovation among heavy polluters than among non-heavy polluters.

Empirical analysis

Data sources

We analyzed annual data on A-share listed companies in China from 2013 to 2020. Corporate green patent data were obtained from the Chinese Research Data Services Platform, while company and regional economic data were drawn from the China Stock Market & Accounting Research Database and the China City Statistical Yearbook. We excluded (1) enterprises with abnormal trading status (ST, *ST, and PT) during the sample period; (2) financial or insurance enterprises, considering their different operations, financing, and so on; (3) enterprises with significant missing data, while missing values were interpolated in some cases; and (4) abnormal values and trimming some continuous variables by 1%. The final sample included 1,862 listed companies and 14,896 observations.

Variable definitions

Explanatory variables

Following Wang and Qi (2016) and Jia and Cui (2020), we used the number of independent green patents by enterprises

TABLE 4 Descriptive statistics of the main variables.

Variable	N	Mean	S.D.	Min	p25	p50	p75	Max
lnGreia	14,896	1.063	1.272	0	0	0.693	1.792	7.319
lnGreInvia	14,896	0.735	1.072	0	0	0	1.099	6.820
Time	14,896	0.375	0.484	0	0	0	1	1
Tax	14,896	0.646	0.478	0	0	1	1	1
Time* tax	14,896	0.244	0.429	0	0	0	0	1
Age	14,896	12.99	6.928	1	7	13	19	27
independ	14,896	0.380	0.073	0.250	0.333	0.364	0.429	0.600
top10	14,896	0.565	0.150	0.230	0.454	0.567	0.672	0.919
sep	14,896	0.048	0.075	0	0	0	0.081	0.283
ROA	14,896	0.046	0.068	−0.303	0.025	0.046	0.075	0.233
TDR	14,896	0.452	0.205	0.059	0.292	0.447	0.604	0.937
tobinq	14,896	0.573	0.514	−0.173	0.184	0.469	0.850	2.293
Cap_inten	14,896	2.721	2.922	0.389	1.340	1.976	3.067	33.66
GDP_3	14,896	0.523	0.113	0.320	0.453	0.503	0.542	0.839
fiscal	14,896	0.030	0.010	0.012	0.023	0.028	0.033	0.068
IEtrade	14,896	6.279	1.939	0.001	5.080	6.616	8.063	8.686
lnSO2	14,896	11.86	1.892	0	11.40	12.10	13.15	14.81

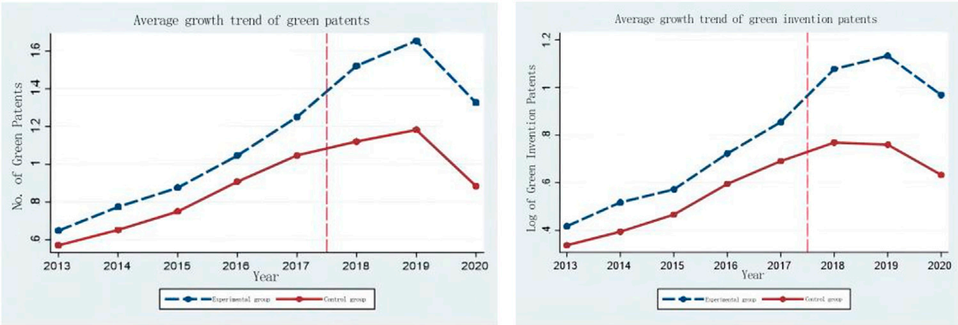

FIGURE 1
Parallel trend test.

TABLE 5 Double-difference full sample regression results.

	(1)	(2)	(3)	(4)
	lnGreia	**lnGreia**	**lnGreInvia**	**lnGreInvia**
time	0.131***(0.030)	0.380***(0.084)	0.131***(0.030)	0.357***(0.072)
tax	−0.014 (0.023)	0.258*(0.088)	−0.014 (0.023)	0.215*(0.073)
Time*tax	0.165***(0.037)	0.151***(0.041)	0.166***(0.037)	0.157***(0.036)
age	−0.010***(0.001)	−0.003**(0.002)	−0.010***(0.001)	0.003**(0.001)
independ	0.385***(0.120)	0.187 (0.130)	0.385***(0.120)	0.286**(0.114)
top10	0.046 (0.060)	0.338***(0.067)	0.046 (0.060)	0.332***(0.058)
sep	0.051 (0.111)	−0.001 (0.125)	0.051 (0.111)	−0.131 (0.107)
ROA	0.829***(0.117)	1.435***(0.137)	0.829***(0.117)	1.128***(0.116)
TDR	0.789***(0.044)	1.291***(0.052)	0.789***(0.044)	0.982***(0.045)
tobinq	−0.175***(0.016)	−0.371***(0.020)	−0.175***(0.016)	−0.263***(0.017)
cap_inten	−0.030***(0.002)	−0.008***(0.003)	−0.030***(0.002)	−0.005**(0.002)
GDP_3	0.857***(0.121)	−0.186 (0.574)	0.857***(0.121)	−0.236 (0.488)
fiscal	8.150***(1.013)	1.499 (1.853)	8.150***(1.013)	1.336 (1.647)
IEtrade	0.036***(0.005)	-0.112**(0.054)	0.036***(0.005)	−0.051 (0.045)
lnSO2	−0.012**(0.006)	0.001 (0.009)	−0.012**(0.006)	0.006 (0.007)
_cons	−0.376***(0.133)	0.399 (0.570)	−0.376***(0.133)	−0.153 (0.488)
Time FE	NO	YES	NO	YES
Province FE	NO	YES	NO	YES
industry FE	NO	YES	NO	YES
R-squared	0.098	0.242	0.098	0.193
Adj-R^2	0.097	0.239	0.097	0.189
N	14,896	14,896	14,896	14,896

Note: Standard errors in parentheses; $^*p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.

TABLE 6 Regression results for the sample by nature of ownership.

	Non-state-owned enterprises		State-owned enterprises	
	(1)	(2)	(3)	(4)
	lnGreia	lnGreInvia	LnGreia	lnGreInvia
time	0.226**(0.111)	0.210**(0.094)	0.562***(0.124)	0.560***(0.107)
tax	0.204**(0.094)	0.161**(0.080)	0.325***(0.103)	0.278***(0.076)
time*tax	0.327***(0.053)	0.269***(0.045)	0.026 (0.061)	0.089 (0.054)
age	-0.009***(0.003)	(0.002) (0.002)	-0.023***(0.003)	-0.016***(0.002)
independ	(0.079) (0.158)	0.066 (0.134)	0.804***(0.206)	0.811***(0.183)
top10	(0.103) (0.089)	(0.089) (0.077)	0.460***(0.102)	0.449***(0.090)
sep	0.615***(0.163)	0.347**(0.136)	-0.411**(0.194)	-0.406**(0.170)
ROA	1.299***(0.158)	0.959***(0.135)	1.595***(0.256)	1.390***(0.218)
TDR	1.022***(0.070)	0.748***(0.059)	1.297***(0.082)	0.987***(0.072)
tobinq	-0.236***(0.025)	-0.149***(0.021)	-0.492***(0.033)	-0.365***(0.029)
cap_inten	(0.001) (0.004)	0.004 (0.003)	-0.012***(0.004)	-0.012***(0.004)
GDP_3	0.060 (0.763)	0.118 (0.651)	0.217 (0.821)	(0.109) (0.701)
fiscal	0.876 (2.317)	0.632 (1.998)	2.869 (2.656)	2.505 (2.380)
IEtrade	(0.108) (0.076)	(0.052) (0.064)	-0.133*(0.073)	(0.076) (0.062)
lnSO2	(0.006) (0.011)	0.007 (0.009)	0.004 (0.014)	0.004 (0.012)
_cons	0.620 (0.757)	(0.087) (0.637)	0.352 (0.816)	0.091 (0.709)
Time FE	YES	YES	YES	YES
Province FE	YES	YES	YES	YES
industry FE	YES	YES	YES	YES
R-squared	0.209	0.152	0.316	0.270
Adj-R^2	0.202	0.144	0.310	0.263
N	7,818	7,818	7,078	7,078

Note: Standard errors in parentheses; $*p < 0.1$, $**p < 0.05$, $***p < 0.01$.

and the number of independent green invention patents applications in the current year to create the indexes of enterprises' green technology innovation level. As the number of green patents may be zero, and given the bias positivity of the patent data, we add 1 to all green patent data, and then take the logarithm.

Explanatory variables

The explanatory variables relate to the environmental protection tax policy implemented from 1 January 2018. This includes the time dummy variable *time*, policy dummy variable *tax*, and interaction term *time*tax*, indicating the net effect of the implementation of this policy. The time dummy variable equals 1 after the policy implementation (2018 and later) and 0 otherwise (before 2018). Following Jin et al. (2020) and Feng et al. (2021), the environmental protection tax is taken as the basis for the policy dummy variable, whether or not the tax levy standard increased. The enterprises located in provinces that raised the tax levy standard after policy implementation (i.e., the tax burden is higher) are the experimental group, whereas the enterprises located in provinces that did not raise it (i.e., the tax burden is flat) are the control group. Thus, the tax equals 0 for the policy dummy variables.

Table 1 presents the levy standards for air pollution and water pollution before and after the tax reform by province. Evidently, for both types of pollution, the tax levy standards increased with sewage charges in some provinces and were unchanged for some others.

Among the 17 provinces and cities, some such as Beijing, Tianjin and Hebei increased the levy standard for two types of pollutants. We used the companies with registered addresses in these locations as the experimental group, where the value of *tax* equals 1. We use others such as Anhui, Liaoning, and Jilin, which did not change their levy standards before and after policy implementation, as the control group. The value of *tax* in this case is 0. Thus, we have 12 provinces and cities for our analysis. Yunnan and Inner Mongolia show dynamic adjustment in the reform of the levy standard; they did not change the levy standard in 2018 but raised it after. Because we use the DID method, and the time dummy variable takes the value of 1, including for 2018 to 2020, we excluded data from these two provinces.

Control variables

Owing to the complexity of the business process, the level of enterprise green innovation is also influenced by various factors. Following Yu and Lianchao (2019) and Fei and Zhang (2020), we select the control variables based on the basic situation and governance structure of the enterprise, the financial status of the enterprise, and the economic development status at the provincial level. Table 2 provides the definitions of the variables.

Model setting

The double-difference score can empirically assess policy effects, making it a popular instrument of measurement in policy studies. In our study, the dummy variable *tax* is a policy variable. We divide the sample into enterprises with a higher tax burden (treatment group) and those with no changes in the tax burden (control group. The dummy variable time is a non-policy time variable based on the formal implementation date of 1 January 2018.

$$Y = \beta_0 + \beta_1 time + \beta_2 tax + \beta_3 time^* tax \quad (1)$$

Model 1 is the basic double-difference model. Table 3 summarizes the meaning of each parameter in this model. The basic principle is that in the control group, the impact coefficient

TABLE 7 Regression results by geographical subsample.

	Eastern region		**Midwest region**	
	(1)	**(2)**	**(3)**	**(4)**
	lnGreia	**lnGreInvia**	**lnGreia**	**lnGreInvia**
Time	0.304**(0.131)	0.334***(0.113)	0.368***(0.124)	0.269***(0.104)
Tax	0.197**(0.099)	0.138*(0.079)	0.244 (0.174)	0.267*(0.150)
time*tax	0.252***(0.060)	0.220***(0.053)	0.042 (0.067)	0.059 (0.057)
Age	0.004**(0.002)	0.010***(0.002)	−0.020***(0.003)	−0.011***(0.002)
Independ	0.091 (0.164)	0.214 (0.145)	0.324 (0.208)	0.385**(0.177)
top10	0.494***(0.086)	0.462***(0.076)	0.007 (0.102)	0.066 (0.084)
sep	(0.085) (0.159)	(0.181) (0.138)	0.295 (0.202)	0.055 (0.167)
ROA	1.625***(0.170)	1.388***(0.145)	0.977***(0.230)	0.552***(0.194)
TDR	1.371***(0.067)	1.073***(0.058)	1.083***(0.082)	0.763***(0.069)
tobinq	−0.337***(0.027)	−0.243***(0.023)	−0.400***(0.029)	−0.276***(0.024)
cap_inten	−0.015***(0.004)	−0.010***(0.003)	(0.002) (0.004)	(0.001) (0.003)
GDP_3	(0.582) (1.108)	(0.842) (0.954)	0.685 (0.760)	0.984 (0.630)
fiscal	0.498 (2.239)	0.657 (1.996)	3.151 (3.672)	4.045 (3.043)
IEtrade	(0.144) (0.148)	(0.060) (0.130)	(0.070) (0.071)	0.002 (0.058)
lnSO2	0.007 (0.015)	0.002 (0.013)	(0.005) (0.011)	0.006 (0.009)
_cons	0.568 (1.570)	0.114 (1.362)	(0.172) (0.422)	−0.701**(0.352)
Time FE	YES	YES	YES	YES
Province FE	YES	YES	YES	YES
industry FE	YES	YES	YES	YES
R-squared	0.261	0.207	0.224	0.176
Adj-R^2	0.257	0.203	0.215	0.166
N	9,976	9,976	4,920	4,920

Note: Standard errors in parentheses; $^*p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.

on green innovation before the tax reform (i.e., the stage of levying emission charges) is β_0. After the tax reform (i.e., the stage of levying environmental protection tax), the impact coefficient on green innovation is $\beta_0 + \beta_1$. At this time, the first-order difference coefficient of the control group before and after the policy implementation is β_1. Similarly, in the experimental group, before the tax reform, the impact coefficient on green innovation is $\beta_0 + \beta_2$, while it is $\beta_0 + \beta_1 + \beta_2 + \beta_3$ after the tax reform. The first-order difference coefficient of the control group before and after the policy is $\beta_1 + \beta_3$. The second-order difference (i.e., the double difference) coefficient β_3 is the net effect of the policy.

To examine the effect on green innovation from the emission fee to tax change, we consider the formal implementation of the policy as an exogenous shock. Based on this quasi-natural experiment, we use the double-difference method to analyze the experimental and control samples. We construct the following model by adding the control variables based on Model 1.

$$Y_{t,i} = \beta_0 + \beta_1 * time_t + \beta_2 * tax_i + \beta_3 * time * tax_i + \beta_4 * control_{i,j} + \varepsilon_{t,i}, \quad (2)$$

where t is time and i is enterprise. The explanatory variable $Y_{t,i}$ is the level of green innovation of enterprises, and comprises the total number of green patents, green invention patents, and green utility model patents; $time_t$ is a time dummy variable, which takes the value 0 before 2018 and 1 in 2018 and later; and tax_i is the policy dummy variable. The interaction term, time $t*tax_i$, measures the net effect of the change in policy. Finally, $control_{i,j}$ is the control variable and $\varepsilon_{t,i}$ is the random disturbance term.

Empirical results and analysis

In this section, we present the descriptive statistics, correlation analysis, parallel trend test, regression analysis of our hypotheses, and subsample analysis.

TABLE 8 Regression results by degree of industry pollution.

	Heavily polluting enterprises		**Non-heavily polluting enterprises**	
	(1)	**(2)**	**(3)**	**(4)**
	lnGreia	**lnGreInvia**	**lnGreia**	**lnGreInvia**
time	0.173 (0.135)	0.142 (0.116)	0.447***(0.105)	0.436***(0.090)
tax	0.309**(0.152)	0.261**(0.130)	0.221**(0.096)	0.181**(0.076)
time*tax	0.335***(0.064)	0.309***(0.057)	0.044 (0.053)	0.074 (0.045)
age	-0.006**(0.003)	0.002 (0.002)	(0.002) (0.002)	0.003*(0.002)
independ	-0.354*(0.195)	(0.138) (0.169)	0.633***(0.174)	0.640***(0.153)
top10	0.000 (0.109)	0.102 (0.095)	0.626***(0.083)	0.544***(0.073)
sep	0.045 (0.197)	(0.100) (0.171)	0.040 (0.161)	(0.104) (0.138)
ROA	1.931***(0.218)	1.522***(0.189)	1.107***(0.175)	0.881***(0.148)
TDR	1.646***(0.085)	1.294***(0.074)	0.999***(0.067)	0.724***(0.057)
tobinq	−0.410***(0.031)	−0.289***(0.027)	−0.363***(0.027)	−0.265***(0.023)
cap_inten	0.001 (0.006)	0.000 (0.005)	−0.014*** (0.003)	−0.009*** (0.002)
GDP_3	0.535 (0.938)	0.968 (0.805)	(0.342) (0.708)	(0.754) (0.600)
fiscal	0.338 (3.071)	(0.605) (2.749)	2.639 (2.289)	2.882 (2.021)
IEtrade	(0.130) (0.086)	(0.074) (0.071)	(0.099) (0.067)	(0.035) (0.057)
lnSO2	0.015 (0.015)	0.014 (0.011)	(0.010) (0.011)	(0.002) (0.009)
_cons	0.484 (0.961)	(0.572) (0.798)	0.335 (0.709)	0.021 (0.606)
Time FE	YES	YES	YES	YES
Province FE	YES	YES	YES	YES
industry FE	YES	YES	YES	YES
R-squared	0.203	0.173	0.293	0.231
Adj-R^2	0.195	0.165	0.287	0.225
N	6,781	6,781	8,115	8,115

Note: Standard errors in parentheses; $*p < 0.1$, $**p < 0.05$, $***p < 0.01$.

Descriptive statistics

Table 4 presents the results of the descriptive statistics of the main variables. The log *lnGreia* of green patents and the log *lnGreInvia* of green invention patents are the explanatory variables. The mean and median of *lnGreia* are 1.063 and 0.693, respectively, with a standard deviation of 1.272; with values ranging from 0 to 7.319. The values of *lnGreInvia* range from 0 to 6.829, with a standard deviation of 1.072, mean of 0.735, and median of 0. These statistics indicate differences between firms in the outcomes of green patents versus invention patents.

The mean and median of the dummy variable *time* are 0.375 and 0, respectively; the mean and median of the dummy variable *tax* are 0.646 and 1, respectively. These results indicate that the experimental group's sample size is marginally bigger than that of the control group. The mean and median of the interaction term *time_tax* are 0.0244 and 0, respectively.

Among the other control variables, the standard deviation of enterprises' listing *age* is 6.928, with larger data, as some enterprises were listed earlier. China's rapid development means the constant listing of new enterprises, making the average listing age shorter, which yields a larger standard deviation. Thus, the standard deviation of asset intensity *cap_inten* reaches 2.721, with larger data, perhaps because of the large differences between industries and the resulting corresponding differences in investment and financing. This leads to similarly larger differences in capital intensity. The mean and median of age (from listing to the present) at *IPOage* and asset intensity *cap_inten*, do not differ much, indicating that they follow a positive distribution. The standard deviations of the remaining control variables are relatively small, and the difference between the mean and median is not large and follows a positive-terrestrial distribution. Further, the distribution of the variables is within the normal range and there are no outliers. Hence, we may continue using the sample data for further analysis.

TABLE 9 Robustness test regression results: Alternative explanatory variable.

	(1)	(2)
	Greia_r	**Greia_r**
Time	0.023***(0.005)	0.064***(0.015)
Tax	0.010**(0.004)	0.032**(0.014)
time*tax	0.029***(0.006)	0.029***(0.007)
Age	−0.003***(0.000)	−0.002***(0.000)
cap_inten	0.001 (0.001)	0.000 (0.001)
ROA	0.058**(0.023)	0.048**(0.023)
top10	−0.057***(0.011)	−0.057***(0.011)
tobinq	−0.025***(0.003)	−0.027***(0.003)
sep	−0.014 (0.020)	0.011 (0.020)
GDP_3	0.056**(0.023)	0.039 (0.097)
fiscal	0.292*(0.173)	0.179 (0.297)
IEtrade	0.001 (0.001)	0.015 (0.009)
lnSO2	−0.003*(0.001)	0.001 (0.002)
independ	−0.038*(0.020)	−0.029 (0.020)
TDR	0.057***(0.009)	0.060***(0.009)
_cons	0.148*** (0.026)	−0.014 (0.098)
Time FE	NO	YES
Province FE	NO	YES
industry FE	NO	YES
R-squared	0.038	0.088
Adj-R^2	0.037	0.083
N	14,896	14,896

Note: Standard errors in parentheses; $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.

Common trend test

We follow Bertrand et al. (2004) to ensure that the data composition of the experimental and control groups satisfy the common trend assumption as an important prerequisite for ensuring the validity of the double-difference estimation. We thus conduct a common trend test of the sample data before the double-difference estimation. Based on the parallel trend hypothesis, the logarithms of green patent applications of enterprises with higher or flat environmental tax burdens are consistent in the time trend before the tax reform policy. In contrast, a significant change in the parallel trends between the experimental and control groups after the tax reform policy indicates that the level of green innovation in the enterprises with higher environmental taxation changed in trend relative to the enterprises with flat taxation.

Figure 1 shows the results of the parallel trend test with the parallel trend plots of log green patents *lnGreia* and log green invention patents *lnGreInvia*. The horizontal axis is the year and the vertical axis is the mean value of the log of green patent applications. Before 2018, the gap between the experimental and control groups for green patents was small, maintaining a relatively parallel growth trend, but increased significantly after 2018. Although the data for both groups show a significant decreasing trend in 2020, the number of green patents in the experimental group continued to increase relative to the control group. Thus, the premise of the parallel trend test hypothesis was met.

TABLE 10 Robustness test regression results: Property rights subsample.

	Non-state-owned enterprises		State-owned enterprises	
	(1)	(2)	(3)	(4)
Time	0.005 (0.007)	0.045**(0.021)	0.045***(0.008)	0.090***(0.021)
Tax	0.014**(0.006)	0.039***(0.012)	0.007 (0.007)	0.008 (0.047)
Time*tax	0.047***(0.008)	0.047***(0.009)	0.015 (0.010)	0.014 (0.010)
Age	−0.002***0.000	−0.002***0.000	−0.005***0.000	−0.005***0.000
cap_inten	(0.016) (0.026)	(0.013) (0.026)	(0.031) (0.032)	0.003 (0.031)
ROA	−0.053***(0.015)	−0.045***(0.015)	−0.075***(0.016)	−0.091***(0.016)
top10	0.013 (0.026)	0.048*(0.026)	(0.013) (0.030)	(0.016) (0.030)
Tobinq	0.024 (0.027)	0.014 (0.027)	0.101**(0.042)	0.086**(0.043)
sep	0.037***(0.012)	0.023*(0.012)	0.060***(0.013)	0.071***(0.014)
GDP_3	−0.024***(0.004)	−0.027***(0.004)	−0.022***(0.005)	−0.027***(0.005)
fiscal	0.002**(0.001)	0.002**(0.001)	(0.001) (0.001)	0.000 (0.001)
IEtrade	0.068**(0.032)	0.042 (0.135)	0.042 (0.033)	0.084 (0.133)
lnSO2	(0.069) (0.253)	0.180 (0.396)	0.462*(0.237)	0.196 (0.425)
independ	0.000 (0.001)	0.002 (0.015)	0.004**(0.001)	0.018 (0.012)
TDR	-0.005***(0.002)	0.001 (0.002)	0.000 (0.002)	0.000 (0.003)
_cons	0.168***(0.037)	0.077 (0.138)	0.157***(0.038)	(0.006) (0.143)
Time FE	NO	YES	NO	YES
Province FE	NO	YES	NO	YES
industry FE	NO	YES	NO	YES
R-squared	0.050	0.099	0.040	0.113
Adj-R2	0.048	0.091	0.038	0.104
N	7,818	7,818	7,078	7,078

Note: Standard errors in parentheses; *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

The significant decline in green patents in both the experimental and control groups in 2020 may be attributed to the effects of the COVID-19 pandemic, which prompted a global economic slowdown. As the virus was first detected in China, its economy was the first to be affected, resulting in a decline in corporate green innovation output. We remove the effect of the epidemic shock on our results to some extent by using the DID method to estimate the effect of the 2018 tax reform on green innovation.

Empirical results

Table 5 shows the results of the double-difference test on Model 2 using the full sample data. Here, (1) and (3) indicate the tests conducted on corporate green patent *lnGreia* and green invention patent *lnGreInvia* without the time, industry, and geographical fixed effects. Models (2) and (4) are the results of the tests with these fixed effects. The regression coefficients of the interaction term *time*tax* in (1) and (3) are 0.165 and 0.166, respectively, and those corresponding to (2) and (4) change to 0.151 and 0.157, respectively. Although the coefficients of the interaction terms become smaller after controlling for fixed effects, both results are significant at the 1% level after controlling for factors that vary with time.

The level of green innovation only slightly decreased after controlling for time, industry, and geographical changes, but the coefficient of the interaction term *time*tax* still indicates that the tax reform significantly promoted green innovation, which supports Hypothesis 1.

The results suggest that although only some regions increased the tax burden based on the original emission charges and others adopted the tax burden-shifting scheme, the 2018 tax reform still sent a strong signal to the market that the state is shifting its focus through greater and increasing stringency in its environmental protection requirement. Therefore, enterprises must carry out green innovation to meet these new requirements and accelerate their transformation and upgrading.

Comparing the coefficients of the interaction terms of green patents *lnGreia* and green invention patents *lnGreInvia* (are 0.165 and 0.151, respectively) reveals that the coefficients of green patent cross each other downward before and after including fixed effects. These values are lower than the coefficients at which green invention patents cross downward; that is, 0.166 and 0.157. The results indicate that the promotion effect of the tax reform is slightly stronger for green invention patents than on the total number of green patents. This may be because green patents include green invention patents and green utility model patents, where the innovation in the former patents is stronger than the latter (Feng et al., 2021). Thus, we conclude that the innovation in the case of green invention patents is stronger than that of overall green patents.

Further analysis

Extending our regression results, we now investigate the heterogenous effects of the tax reform on green innovation based on property rights, geography, and industry pollution. Following the above findings, we conduct all further tests by controlling for time, industry, and province fixed effects.

Property rights

In China, firms are classified as either SOEs or non-SOEs. We therefore find large disparities in operations and management between these types of enterprises. We divide the sample into SOEs and non-SOEs to further test the effect of the tax reform on green innovation according to ownership type.

Table 6 presents the results. The coefficients of the interaction term *time*tax* in columns (1) and (2) for non-SOEs are 0.327 and 0.269, respectively, and are significant at

TABLE 11 Robustness test regression results: Regional subsamples.

	Eastern region		Midwest region	
	(1)	(2)	(3)	(4)
time	0.021***(0.008)	0.050**(0.022)	0.000 (0.009)	0.077***(0.023)
tax	0.017***(0.006)	0.033*(0.019)	(0.001) (0.007)	0.019 (0.015)
time*tax	0.036***(0.009)	0.032***(0.009)	0.013 (0.011)	0.011 (0.011)
age	−0.002***0.000	−0.002***0.000	−0.004***0.000	−0.004***0.000
cap_inten	(0.030) (0.025)	(0.019) (0.024)	(0.040) (0.034)	(0.039) (0.034)
ROA	−0.062***(0.013)	−0.062***(0.013)	−0.047***(0.017)	−0.046**(0.018)
top10	(0.016) (0.025)	0.023 (0.025)	(0.007) (0.032)	(0.018) (0.031)
tobinq	0.067**(0.028)	0.048*(0.027)	0.046 (0.042)	0.031 (0.042)
sep	0.062***(0.011)	0.057***(0.011)	0.049***(0.014)	0.052***(0.015)
GDP_3	−0.023***(0.004)	−0.023***(0.004)	−0.029***(0.005)	−0.033***(0.005)
fiscal	0.001 (0.001)	(0.001) (0.001)	0.001 (0.001)	0.001 (0.001)
IEtrade	0.038 (0.034)	0.104 (0.179)	0.384***(0.064)	0.007 (0.134)
lnSO2	0.356 (0.218)	0.224 (0.363)	(0.092) (0.336)	(0.203) (0.590)
independ	(0.003) (0.003)	0.011 (0.027)	0.006***(0.002)	0.013 (0.012)
TDR	(0.001) (0.002)	0.001 (0.003)	−0.003**(0.002)	0.000 (0.002)
_cons	0.151***(0.045)	(0.039) (0.283)	0.032 (0.042)	0.154**(0.075)
Time FE	NO	YES	NO	YES
Province FE	NO	YES	NO	YES
industry FE	NO	YES	NO	YES
R-squared	0.039	0.120	0.039	0.082
Adj-R^2	0.037	0.115	0.036	0.071
N	9,976	9,976	4,920	4,920

Note: Standard errors in parentheses; *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

TABLE 12 Robustness test regression results: Degree of industry pollution.

	Heavy pollution industry		Non-heavy pollution industry	
	(1)	(2)	(3)	(4)
time	0.009 (0.007)	0.049**(0.020)	0.033***(0.008)	0.073***(0.021)
tax	0.003 (0.006)	0.023 (0.016)	0.017***(0.006)	0.037*(0.021)
time*tax	0.049***(0.008)	0.047***(0.009)	0.014 (0.009)	0.015 (0.010)
age	−0.003***0.000	−0.003***0.000	−0.002***0.000	−0.001***0.000
cap_inten	−0.064**(0.026)	−0.059**(0.026)	(0.003) (0.030)	0.002 (0.030)
ROA	−0.077***(0.015)	−0.085***(0.015)	−0.050***(0.015)	−0.044***(0.015)
top10	(0.032) (0.026)	0.000 (0.026)	0.012 (0.029)	0.034 (0.030)
tobinq	0.030 (0.030)	0.023 (0.031)	0.083** (0.035)	0.077**(0.035)
sep	0.092***(0.013)	0.092***(0.012)	0.028**(0.012)	0.039***(0.013)
GDP_3	−0.021***(0.004)	−0.028***(0.005)	−0.025***(0.005)	-0.026***(0.005)
fiscal	0.004***(0.001)	0.004***(0.001)	(0.001) (0.001)	(0.001) (0.001)
IEtrade	0.083***(0.029)	0.048 (0.131)	0.018 (0.032)	0.015 (0.136)
lnSO2	−0.533**(0.233)	0.130 (0.397)	0.812***(0.243)	0.090(0.419)
independ	0.000 (0.001)	0.029**(0.013)	0.002 (0.001)	0.002 (0.013)
TDR	(0.001)(0.002)	0.001(0.002)	−0.004**(0.002)	0.000(0.003)
_cons	0.144***(0.033)	0.713***(0.137)	0.163***(0.038)	0.073(0.137)
Time FE	NO	YES	NO	YES
Province FE	NO	YES	NO	YES
industry FE	NO	YES	NO	YES
R-squared	0.055	0.094	0.034	0.102
Adj-R2	0.053	0.085	0.032	0.095
N	6,781	6,781	8,115	8,115

Note: Standard errors in parentheses; *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

the 1% level. The coefficients of the interaction term *time*tax* in columns (3) and (4) for SOEs are 0.026 and 0.089, respectively, but insignificant. Thus, the tax reform has a more significant contribution to the number of green invention patents among non-SOEs than SOEs, supporting Hypothesis 2. We surmise that our regression results reflect the stronger innovation capabilities of non-SOEs. SOEs, having better access to resources because of their relationship with the government, have less incentive toward green innovation. Consequently, non-SOEs show stronger green innovation ability and responded faster to the tax reform.

Regional heterogeneity

The economic conditions and development levels across provinces in China vary greatly. Hence, each province sets its own environmental tax levies that reflect its specific conditions, but within the scope of the Law. Logically then, the effects on green innovation also vary by geography.

We divide the sample into two subsamples: the eastern and central-western regions of China. Table 7 presents the results of the regression tests. For the eastern region, the coefficients of the interaction term *time*tax* in (1) and (2) are 0.252 and 0.220, respectively, and significant at the 1% level. For the central and western regions, the coefficients of the interaction term *time*tax* in (3) and (4) regressions are insignificant at 0.042 and 0.059, respectively. Both coefficients of the interaction term and the significance levels indicate that the 2018 tax reform significantly promoted green innovation in the eastern region relative to the central and western regions.

This disparity is easy to explain—China's eastern region is far more developed, with an overall higher standard of environmental tax levy. This condition promotes a stronger willingness among enterprises to conduct green innovation, which reduces pollution emissions and thus environmental taxes. Such enterprises can then move on to the next stage of transforming and upgrading themselves structures on the path to long-term development.

Heterogeneity in degree of industry pollution

Post tax-reform, polluting enterprises face the burden of the new tax levies. Heavy polluters whose emissions are high throughout the production and operation processes are especially hit hard. Their need for green upgrades to keep pace with national development is thus more urgent, and their willingness to conduct green innovation relatively strong.

According to the degree of pollution of the industry, we divide our enterprise sample into heavily polluting and non-heavily polluting industries for the DID estimation. Our categorization is based on the management list of the environmental verification industry classification for listed companies and the guidelines of environmental information disclosure for listed companies.

Table 8 presents the regression results. The coefficients of the interaction term *time*tax*, which reflect the net effect of the policy, for green patents (1) and green invention patents (2) are 0.335 and 0.309, respectively, for heavy polluters, and significant at the 5% level. The regression coefficients of green patents (3) and green invention patents (4) for non-heavily polluting enterprises are 0.044 and 0.074, respectively, but insignificant. Thus, the effect of the tax reform on promoting green innovation is more significant among heavily polluting enterprises than among less heavily polluting enterprises. As noted earlier, heavy polluters produce more pollutants within the scope of environmental taxation, so the tax reform has a greater effect on them. As environmental tax costs increase more in provinces that raised the tax burden, the role of the tax reform in forcing heavy polluters to conduct green innovation and upgrade their processes is more significant.

Robustness tests

Full sample

To ensure the accuracy and reliability of our results, we conduct a robustness test using an alternative measure for the explanatory variables. Following Popp (Fei and Zhang, 2020) and Xu and Cui (Tao et al., 2021), we adopt the ratio of green patents independently filed by enterprises in the current year to the total independently filed patents in the current year (*Greia_r*) as an alternative measure, and then perform the DID estimation in Model 2.

Table 9 presents the regression results. Columns (1) and (2) present the results for Model 2 without and with the time, industry, and province fixed effects. The regression coefficients of the interaction term *time*tax* in both (1) and (2) are 0.029, and significant at the 1% level. After considering the effects of the other control variables and time, industry, and province fixed effects, we find that the tax reform still promotes corporate green innovation. This conclusion confirms the original regression results and supports Hypothesis 1. Thus, our results are robust.

Property rights

Based on the robustness check of the main regression, we conduct a second test for the subsample divided by property rights. Table 10 presents the regression results. The coefficients of the interaction term *time*tax* in columns (1) and (2) are 0.047 and 0.047 for non-SOEs, and significant at the 1% level. In contrast, the coefficient for non-SOEs is insignificant. These results confirm Hypothesis 2 and the robustness of the main results.

Geographical heterogeneity

Table 11 presents the regression results of the robustness test for the geographical subsample. Here, (1) and (3) are the regression results without the time, industry, and province fixed effects, and (2) and (4) are the results with these fixed effects. The coefficients of the interaction term *time*tax* in columns (1) and (2) for the eastern region are 0.036 and 0.032, respectively, and significant at the 1% level without the fixed effects. In contrast, the coefficients of *time_tax* in columns (3) and (4) for the western region in China are 0.013 and 0.011, but insignificant. These findings confirm that our regression results for geographical heterogeneity are robust, lending further support to Hypothesis 3.

Degree of industry pollution

Table 12 presents the robustness test results for the subsamples based on degree of industry pollution. As with the previous subsample tests, (1) and (3) present the results without the time, industry, and province fixed effects, and (2) and (4) present the results with these fixed effects. The coefficients of the interaction term *time*tax* in the heavily polluting industries are 0.049 and 0.047, respectively, and significant at the 1% level. The coefficients of *time*tax* in the non-heavily polluting industries are 0.014 and 0.015, respectively, but insignificant. Thus, the tax reform affected heavy polluters more in terms of promoting green innovation capability, supporting Hypothesis 4 and confirming the robustness of the main results.

Conclusion

The 2018 environmental tax reform in China marked a paradigm shift away from emissions fees toward taxation to foster an "ecological civilization" in an era of rapid climate change and increasing pollution. This new regulatory regime ends 4 decades of the emissions fee system and further modernizes China's environmental protection framework. We used this tax reform as a quasi-natural experiment to study its effect on enterprises' green technological innovation under different conditions that reflect the regional heterogeneity of the country. Our results are summarized below.

Overall, the tax reform has a significant promotion effect on green innovation that is stronger for green invention patents, reflects how this category is generally more innovative than green utility model patents. The subsample regression on enterprises property rights shows that the promotion effect is stronger for non-SOEs than for SOEs, and this finding holds for all green patent data and green invention patents. Thus, non-SOEs responded to the tax reform with greater urgency and jumpstarted green innovation to benefit from the new tax regime. The regional analysis shows that the promotion effect is stronger in the eastern region than in the central and western regions, which reflects the former's relatively advanced economies and industries. Enterprises in these regions have the resources to innovate and greater motivation to engage in green motivation as the tax levied on them is greater and environmental control is stricter. Finally, we examine the degree of industry pollution and find that the tax reform had a greater effect on heavy polluters, thereby increasing the promotion effect of green innovation. These industries face greater environmental tax costs, higher penalties, and stronger demand for green innovation. Similarly, the promotion effect on the more innovative green invention patents is more significant relative to the total green patent data.

Limitations

Although we expand the literature on environmental tax reform, our study has some limitations. First, green innovation is a complex, wide-ranging, and comprehensive indicator. Owing to the availability and operability of empirical data, we used enterprises' annual green patent applications to measure their green innovation, but such data have limitations. Future research can expand on the measurement of green innovation capability and use more comprehensive and representative data.

Second, in terms of quantifying this indicator of environmental tax reform, we considered only whether the new environmental tax burden standard increased or shifted based on the original emissions fee system. We did not analyze the effect of the *degree* of increase in the tax burden on green innovation specifically. The threshold of the increase in the tax burden requires further study. For example, future research can examine the degree of the environmental tax levy increase and its effect on green innovation by increasing the same or similar standards under different emission fee levy standards.

Third, we studied only the effect of changes in environmental tax burden standards on green innovation, but ignored intrinsic relationships such as its impact path and mechanism of action. Exploring these aspects should further enrich the study and increase its theoretical depth.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

Conceptualization, CZ and CFZ; methodology, CFZ; software, WL; validation, CFZ, WL, and LL; formal analysis, CZ; investigation, CFZ and LL; resources, CZ; data curation, CFZ; writing—original draft preparation, CFZ and LL; writing—review and editing, CFZ and WL; visualization, CZ; supervision, CZ; project administration, CZ; funding acquisition, CZ. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.1036810/full#supplementary-material

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frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 07 November 2022
DOI 10.3389/fenvs.2022.1032586

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OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Environmental Economics and Management,
a section of the journal Frontiers in Environmental Science

RECEIVED 31 August 2022
ACCEPTED 21 October 2022
PUBLISHED 07 November 2022

CITATION
Li C, Chen Z, Wu Y, Zuo X, Jin H, Xu Y, Zeng B, Zhao G and Wan Y (2022), Impact of green finance on China's high-quality economic development, environmental pollution, and energy consumption.
Front. Environ. Sci. 10:1032586.
doi: 10.3389/fenvs.2022.1032586

Impact of green finance on China's high-quality economic development, environmental pollution, and energy consumption

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Green finance is an important practice of China's high-quality economic development in the new era, which is closely related to economic development, environment, and energy conditions. However, few studies systematically analyze the impact of green finance on economic development, environmental pollution, and energy consumption, especially on China which is turning to high-quality economic development. In order to fill the gap, based on the annual data on 30 provinces (autonomous regions and municipalities) in China from 2008 to 2018, we construct a comparatively comprehensive green finance index system and use a panel regression model to explore the impacts of green finance on high-quality economic development, environmental pollution, and energy consumption. We find that green finance can significantly promote high-quality economic development, mitigate environmental pollution, and reduce energy consumption. There is spatial and temporal heterogeneity in the impact of green finance on China's economic quality, environmental pollution, and energy consumption. In the eastern region, green finance has a remarkable positive impact on high-quality economic development and a significant negative impact on energy consumption, but the impact on environmental pollution is inconspicuous. In the central region, green finance has a prominent effect on reducing environmental pollution, but the impact on high-quality economic development and energy consumption is not significant. In the western region, green finance has not been able to significantly promote high-quality economic development, mitigate environmental pollution, and reduce energy consumption. After the clear proposal of green finance, the role of green finance in promoting a high-quality economy has enhanced, and the role of green finance in reducing environmental pollution and energy consumption has decreased. This study can provide a useful decision-making reference for promoting high-quality economic development, reducing environmental pollution and energy consumption, and spurring sustainable development.

KEYWORDS

green finance, high-quality economic development, environmental pollution, energy consumption, heterogeneity

1 Introduction

In the Integrated Reform Plan for Promoting Ecological Progress which was issued in September 2015, Article 45 clearly stated for the first time that "we should establish a green financial system in China." In the proposal of the 13th Five-Year Plan, the Central Committee of the Communist Party of China once again explicitly proposed to develop green finance. Green finance has been upgraded to a national strategic goal and development plan, which shows that China attaches great importance to green finance. In 2017, the report of the 19th National Congress of the Communist Party of China (NCCPC) pointed out that China's economy has shifted from a stage of high-speed growth to a stage of high-quality development. At this stage, the high-quality development strategy should be firmly implemented. The report also emphasizes the coordination and progress of the five dimensions, namely, economy, society, politics, ecology, and culture, and it focuses on solving key problems such as the optimization of industrial structure, the growth of productivity, and the development of power transformation. However, the current comprehensive development of China's economy, environment, and energy is not coordinated enough, and new requirements are put forward for energy consumption, environmental pollution, and other resource and environmental problems in this report. At the same time, realizing the transformation of economic growth momentum and the expected emission reduction targets is also an important task for China to achieve high-quality and coordinated development. Therefore, it is a question worth exploring whether the development of green finance can promote high-quality economic development, mitigate environmental pollution, and reduce energy consumption in China.

The existing literature provides evidence for this study. Many scholars have expounded and explained the connotation of green finance. The concept of green finance originates from various economies' growing concern for environmental protection and adaptation to climate change, which is a financial innovation that supports the transformation of a green economy (Bhatnagar and Sharma, 2022). Since green finance connects the financial industry, environmental improvement, and economic growth (Soundarrajan and Vivek, 2016), it is not only conducive to environmental protection but can also build a better world for our future (Jayasubramanian and Shanthi, 2014). However, some scholars believe that green finance inhibits green innovation capacity (Yu et al., 2021). The outbreak of COVID-19 has had a great impact on countries around the world. Therefore, some scholars believe that the green financial system needs to consider the impact of COVID-19 on investment in green projects (Farhad et al., 2021). Green finance, closely related to economic development, is important to countries at different levels of sustainable development (Djukic and Ilic, 2021). In order to achieve sustainable economic growth, it is necessary to evaluate green finance more rationally and quantitatively (Alieva and Altunina, 2021). Ecological environment protection and economic development can be effectively linked by further analyzing the coordination quantitatively between green finance and economic growth (Yin and Xu, 2022). Now, green finance has become a tool for coping with climate change, which can help solve the problems of financial products and services which are related to the environment (Gagan et al., 2022). In light of the development of financial technology, the positive impact of green finance on environmental protection has greatly increased (Sreenu, 2022). Considering the impact of monetary policy from a macro perspective, a global perspective will be adopted to solve the problem between green finance and the environment (EWA and Johannes, 2021). The development of a digital economy plays an important role in the process that green finance helps reduce carbon emissions of the environment (Zhang et al., 2022). By incorporating spatial geographical factors into the analysis, green finance has a significant spatial spillover effect on environmental improvement and is beneficial to the ecological environment of surrounding areas (Li and Gan, 2020; Li et al., 2022). Green finance is closely related to the sustainable development of energy. Whether from the perspective of a horizontal comparison or vertical trend, green finance can promote energy development (Zhang and Wang, 2019). There is risk transmission between green financial products and energy commodity markets (Hela et al., 2022), and reducing green financial risks will help increase the revenue of green energy projects (Farhad and Naoyuki, 2019). Green finance can help realize energy transformation and promote the demand for clean energy (Mara et al., 2022). At the same time, the development of green finance has promoted the realization of China's sustainable development goals and has greatly improved the environmental emergencies caused by the crude model of past economic development and earlier improper sustainability management (Bryan et al., 2018; Sun et al., 2018).

Through the literature review, we can find that although the literature on green finance is rich, most of them are about the connotation of green finance or related to economy and there are few literature reports related to the environment and energy. At the same time, there are fewer literature reports systematically and deeply studying the relationship between green finance, economy, environment, and energy. On one hand, systematically exploring the impact of green finance is conducive to promoting the high-quality, comprehensive, and coordinated development of China's economy, environment, and energy; on the other hand, it deeply studies the spatial and temporal heterogeneity of the impact of green finance and provides Chinese experience for the coordinated development of world green finance.

In order to make up for the shortcomings of the aforementioned research studies, we mainly study the following two questions about the impact of green finance. First, is the impact of green finance on the economy, environment, and energy beneficial? Second, is the impact of green finance heterogeneous spatially and temporally? Solving the aforementioned questions is very important for China's green financial development and comprehensive and coordinated development. At the same time, it has practical reference significance for promoting the development of green finance and the coordinated development of economy, environment, and energy in various countries and fills the academic gaps in the study of the relationship between green finance, economy, environment, and energy in terms of system and spatial and temporal heterogeneity.

To answer the aforementioned questions and distinguish from other works of literature, taking the annual data on 30 provinces and municipalities directly under the central government and autonomous regions (excluding Tibet, Hong Kong, Macao, and Taiwan) in China from 2008 to 2018 as a research sample, this study constructs a relatively comprehensive green finance index system. A panel regression model is used to examine whether green finance can promote high-quality economic development, mitigate environmental pollution, and reduce energy consumption, and further investigate the spatial and temporal heterogeneity of the impact of green finance on the economy, environment, and energy.

The contribution of this study is mainly reflected in two aspects. First, we have built a relatively comprehensive evaluation index of green finance and high-quality economic development. We consider green finance from the five dimensions, namely, green credit, green securities, green investment, green insurance, and carbon finance. We also select 20 variables from the five dimensions, namely, innovation, coordination, green, openness, and sharing to consider the high-quality development of the economy. The description of green finance and a high-quality economy is relatively comprehensive. Second, we systematically and deeply examine the impact of green finance on economic quality, environmental pollution, and energy consumption, as well as the spatial and temporal heterogeneity.

The rest of the study is arranged as follows: the second section is the model and data, including model construction, variable selection, and data description. The third section is the results, including descriptive statistics of variables, spatial–temporal evolution analysis, benchmark regression results, heterogeneity analysis, and the robustness test. The fourth section is discussion, which combines relevant theories with the reality of China and discusses the results of the study. The fifth section is the conclusion and implications, which summarizes the research results of this study and puts forward corresponding research implications.

2 Model and data

2.1 Panel data model

A panel data model is used to examine whether the development of green finance has a significant impact on the high-quality development of China's economy, environmental pollution, and energy consumption. Therefore, this study uses the panel data on 30 provinces (autonomous regions and municipalities) in China from 2008 to 2018 to study the relationship between green finance, high-quality economy, environmental pollution, and energy consumption. The model is shown in Formula (1):

$$Y_{it} = \beta_0 + \beta_1 LJ_{it} + \beta_2 X_{it} + \mu_i + \delta_t + \varepsilon_{it}. \quad (1)$$

In this formula, Y_{it} is the interpreted variable, which indicates the high-quality economic development level, environmental pollution status, and energy consumption of the ith province in year t; LJ_{it} indicates the green finance level of the ith province in the year t; X_{it} indicates the control variables, including industrial structure, urbanization, government intervention, technological progress, resident income, and foreign direct investment; μ_i indicates the individual fixed effect; δ_t represents the time fixed effect; and ε_{it} represents the error term.

2.2 Variable selection

2.2.1 Explained variable

At present, the measurement standard of high-quality economic development in academic circles has not reached a unified level. Considering portraying the high-quality economic development concept as much as possible, the authors refer to the research studies of Wei and Li (2018), Zeng et al. (2019), Zhao et al. (2020), and Cheng and Xia (2021). Based on the five dimensions of the five development concepts, namely, innovation, coordination, green, openness, and sharing, the authors use the entropy method to construct high-quality economic development indicators. The specific indicators are shown in Supplementary Table S1.

The construction of high-quality economic indicators is, first, about innovation. “Innovative” development focuses on the issue of development power. Based on the three perspectives of innovation input, innovation output, and innovation contribution, the authors select variables to measure the connotation of “innovation.” Second, it is about coordination. “Coordinated” development focuses on imbalances in development. Based on the three perspectives of regional coordination, urban–rural coordination, and structural coordination, this study selects variables to measure the connotation of “coordination.” Third, it is about green. The “green” concept focuses on investigating the impact of production activities on the natural environment. Based on the three perspectives of environmental pollution, resource consumption, and greening, this study selects variables to measure the connotation of “green.” Fourth, it is about openness. “Open” development focuses on internal and external linkage. Based on the three perspectives of the open environment, open degree, and open performance, the authors select variables to measure the connotation of “openness.” Fifth, it is about sharing. The concept of “sharing” focuses on the distribution of social welfare and the quality of people’s life. Based on the three perspectives of public service, people’s livelihood quality, and people’s life, this study selects variables to measure the connotation of “sharing.”

As for the environmental pollution indicators, three secondary indicators, namely, carbon emission, PM2.5, and industrial dust are selected, and the entropy method is used to construct the total environmental pollution indicators. Among them, the carbon emission index refers to the practice of Shan et al. (2018), which calculates the carbon dioxide emission data generated by the combustion of fossil fuels (raw coal, crude oil, and natural gas) from top to bottom using the statistical data on energy supply, and it also follows the emission accounting method of the Intergovernmental Panel on Climate Change (IPCC). The measurement method is the apparent emission accounting method. For PM2.5 and industrial dust, the annual average concentration of fine particles and industrial dust emission is selected. As for energy consumption indicators, the authors refer to the practices of most scholars and select the logarithm of energy consumption in each region.

2.2.2 Core explanatory variable

In 2007, the State Environmental Protection Administration, the People’s Bank of China, and the China Bank Regulatory Commission jointly issued opinions on implementing environmental protection policies and regulations to prevent credit risks and formally issued the green credit policy. In 2008, the Industrial Bank officially announced the adoption of the “Equator Principle,” which became the first Equator Bank in China. Therefore, it can be considered that China’s green finance practice began in 2008. By referring to the existing literature and the availability of data, we set the research scope as 2008–2018. In addition, since the measurement variables of green finance have not been unified yet, the entropy method was used to synthesize the green finance indicator in this study. The specific indicator selection and definition are shown in Supplementary Table S2.

Regarding the construction of green finance, referring to Gao and Zhang (2021)and Zhou et al. (2021), we build indicators from five aspects. First, it is about green credit. It is considered to measure green credit with the variable of interest payment proportions of high energy-consuming enterprises, among which, the high energy-consuming industries include the petroleum processing and coking industry, nuclear fuel processing industry, chemical raw materials and chemical product manufacturing industry, non-metallic mineral product industry, ferrous metal smelting and rolling processing industry, non-ferrous metal smelting and rolling processing industry, and electricity and heat production and supply industry. Since the latest data on enterprise interest payments are in 2018, data collection ended in 2018. Second, it is about green securities. Due to the availability of data, the variable of the market value of high energy-consuming industries is selected to measure green securities. Third, it is about green investment. The authors plan to measure green investment with the variable of the proportion of energy conservation and environmental protection expenditure. Fourth, it is about green insurance. Environmental liability insurance is an important part of green insurance. However, since environmental liability insurance was implemented in China in 2013, considering the time range of the study, the authors select two variables, namely, the proportion of the agricultural insurance scale and the compensation ratio of agricultural insurance, to measure green insurance. Fifth, it is about carbon finance. Referring to most practices of existing research, carbon finance is measured by carbon intensity variables.

2.2.3 Control variable

As for the selection of control variables in formula (1), this study refers to the common practice of domestic scholars and selects six variables: the urbanization level, government intervention, technological progress, foreign direct investment, industrial structure, and resident income level. Among them, the urbanization level indicator is characterized by the proportion of the number of urban people in the total number of people, government intervention is characterized by the proportion of fiscal expenditure in the GDP, technological progress is characterized by the logarithm of the number of patents applied for authorization, foreign direct investment is characterized by the logarithm of foreign direct investment in each province, the industrial structure is characterized by the ratio of the second industry to the total output value, and the resident income level is described by the logarithm of the per capita disposable income of regional residents. The specific control variables are shown in Table 1.

TABLE 1 Control variable.

Variable name	Symbol	Index connotation
Urbanization level	CZH	Proportion of urban population to total population
Government intervention	GY	Proportion of fiscal expenditure to GDP
Technological progress	JS	Logarithm of the number of patents applied for authorization
Foreign direct investment	FDI	Logarithm of foreign direct investment
Industrial structure	CY	Proportion of the secondary industry in the total output value
Resident income level	SR	Logarithm of the per capita disposable income of residents

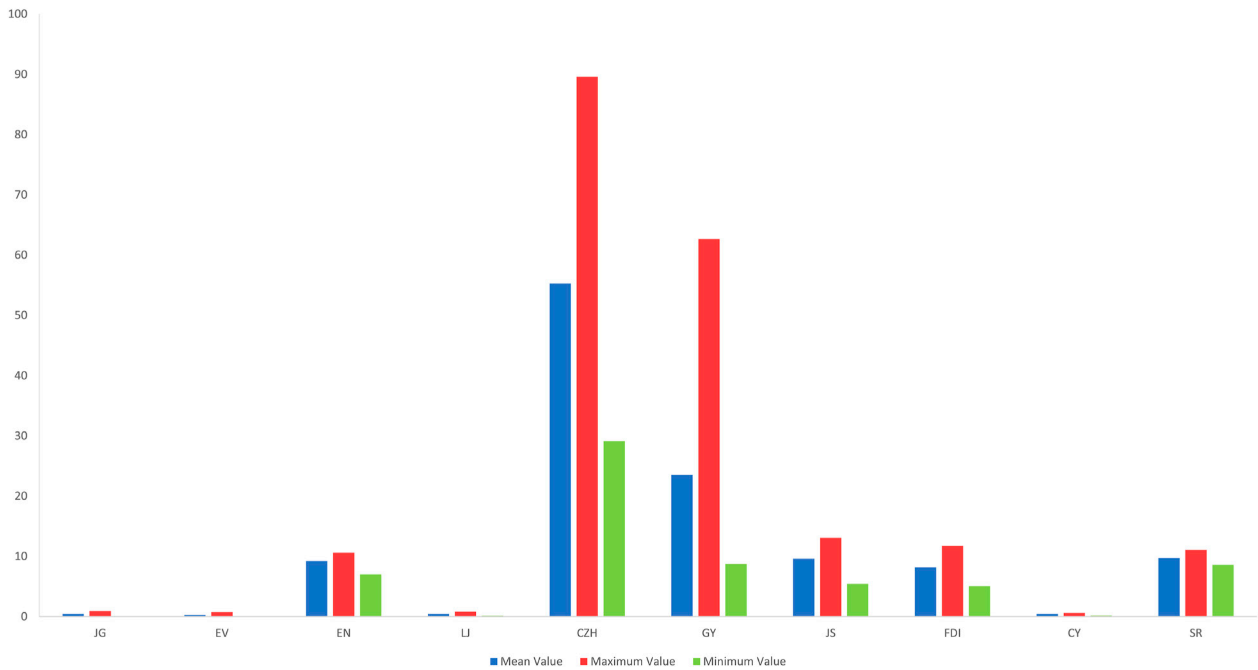

FIGURE 1
Descriptive statistical results.

3 Results

3.1 Descriptive statistics

For the variables involved in this study, the descriptive statistical results are shown in Figure 1. According to Figure 1, it can be seen that there is a big difference between the minimum and maximum values of high-quality economy, environmental pollution, energy consumption, and green finance. It can be inferred that the high-quality economic development level, environmental pollution, energy consumption, and the development level of green finance show an increasing trend over time, and there are significant differences between different provinces (autonomous regions and municipalities) (see Supplementary Table S3 for detailed results).

3.2 Analysis of spatial and temporal evolution

Figure 2 shows the evolution of green finance in various regions of China over time. Before green finance was clearly put forward (2008 and 2012), the development level of green finance in various regions of China was generally low, showing an increasing trend from the central and eastern regions to the southwest. Among them, Sichuan and Zhejiang provinces had the fastest growth rate. After the clear proposal of green finance (2015 and 2018), the development level of green finance in most regions of China has significantly improved and the regions with high development levels are still concentrated in the southwest. In terms of regional difference, the development level of the eastern region is the lowest and the most stable, while the

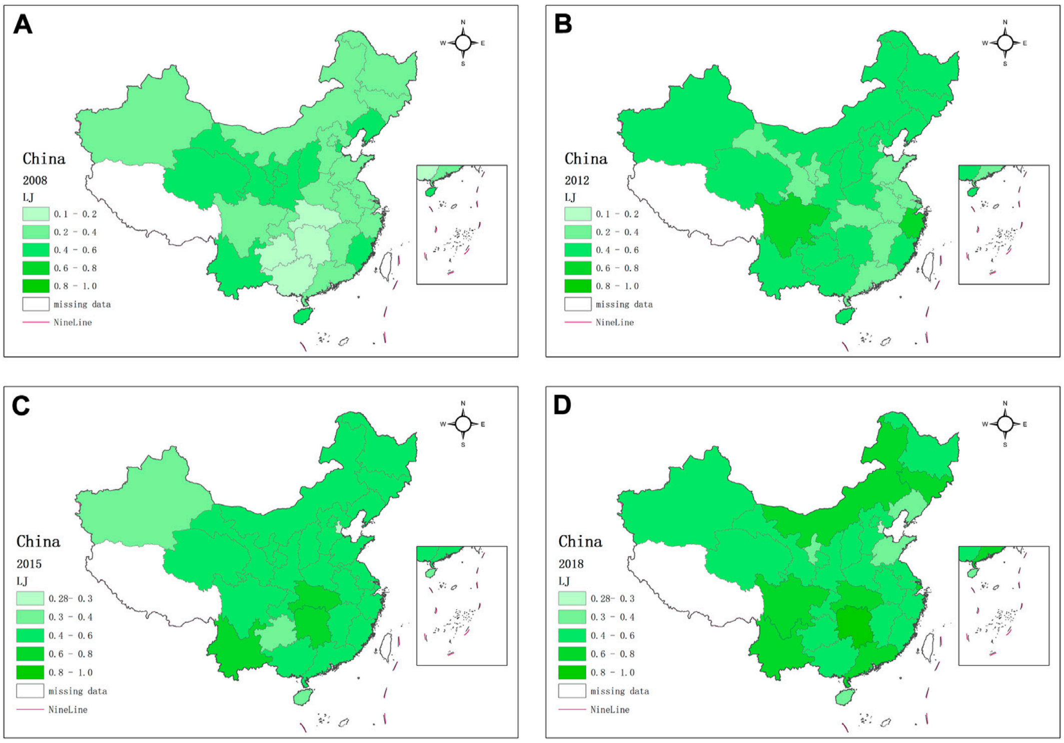

FIGURE 2
Spatial and temporal evolution of green finance.

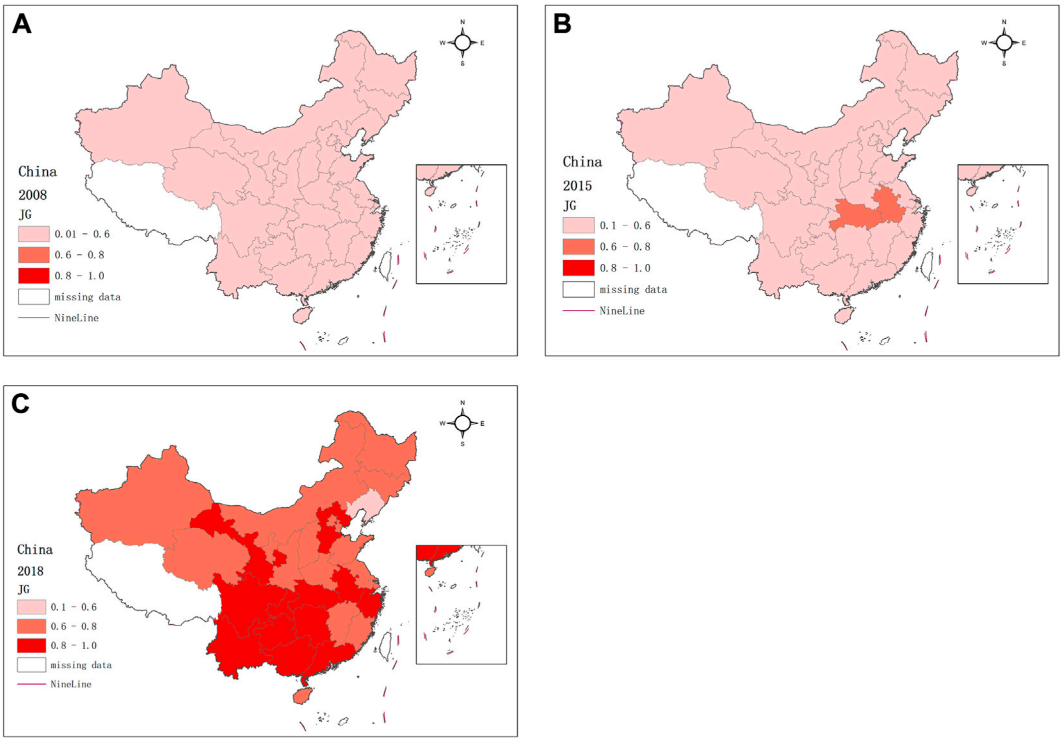

FIGURE 3
Spatial and temporal evolution of high-quality economic development.

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development level of the western region is high but unstable. In terms of time difference, before green finance was clearly proposed, the overall development level of green finance in China was low; after the proposal, the development level of green finance in China has significantly improved.

Figure 3 shows the evolution of high-quality economic development in various regions of China over time. At the early stage of studying the sample (2008), China's high-quality economic development level was at a low level. In the middle period of studying the sample (2015), the high-quality economic development level of each region was still low, and only Anhui and Hubei provinces were at a relatively high level of development. At the end of studying the sample (2018), the level of high-quality economic development across China enhanced rapidly, showing the characteristics of being high in the south and low in the north. Observing the time–space evolution of a high-quality economy, it is found that there is an obvious time difference which shows a trend of rapid development after 2015.

Figure 4 shows the evolution of environmental pollution in various regions of China over time. At the early stage of studying the sample (2008), the environmental pollution level in China was not high on the whole, but it showed obvious regional differences. The pollution level in Southeast China was relatively higher. In the middle period of studying the sample (2015), the environmental pollution level of various regions in China improved, and the regions with relatively high environmental pollution levels were concentrated in Beijing, Tianjin, and Hebei provinces. At the end of studying the sample (2018), the environmental pollution level in some areas decreased significantly, especially in Beijing, Tianjin, and Hebei provinces and their surrounding areas. On the whole, China's environmental pollution shows a development trend of increasing first and then decreasing with time. Regionally, there is a downward trend of diffusion from Beijing, Tianjin, and Hebei provinces to their surrounding areas.

Figure 5 shows the evolution of energy consumption in various regions of China over time. At the early stage of studying the sample (2008), China's energy consumption level was relatively high, with a decreasing trend from the eastern coastal areas to the inland. In the middle period of studying the sample (2015), the energy consumption level of various regions in China improved, especially in the southwest region. At the end of studying the sample (2018), the energy consumption level in most areas of China continued to increase, and the northeast and coastal areas reached the same energy consumption level. On the whole, China's energy consumption is in a state of continuous rise, and the concentration areas with high energy consumption have spread from the eastern coastal areas to the inland.

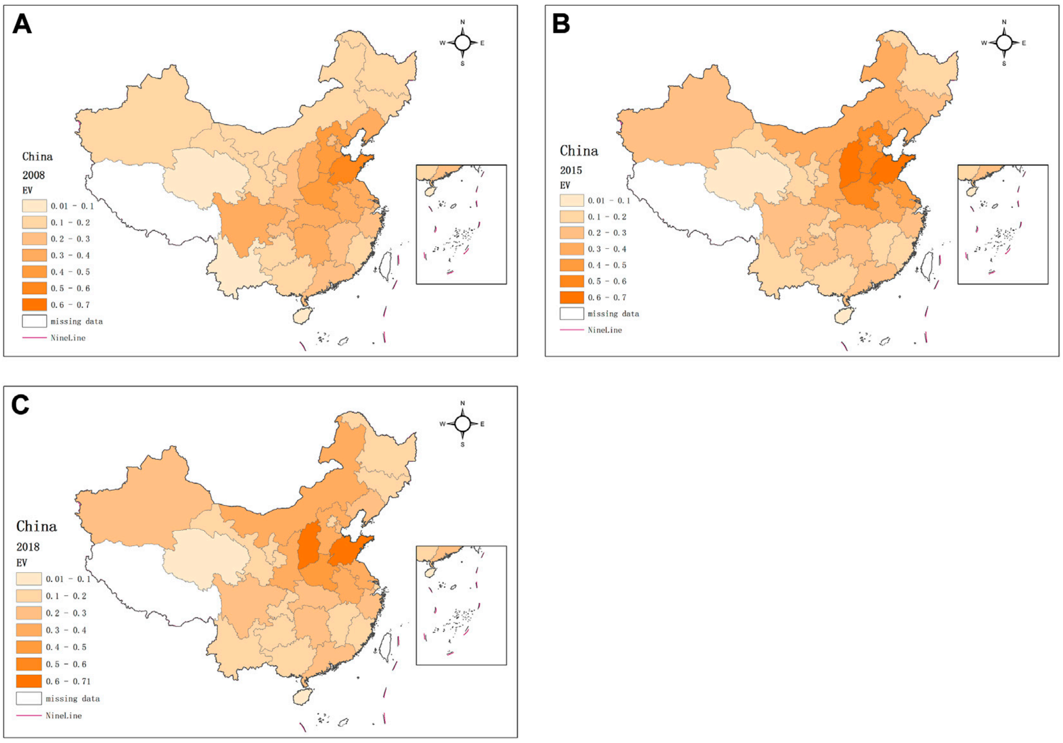

FIGURE 4
Spatial and temporal evolution of environmental pollution.

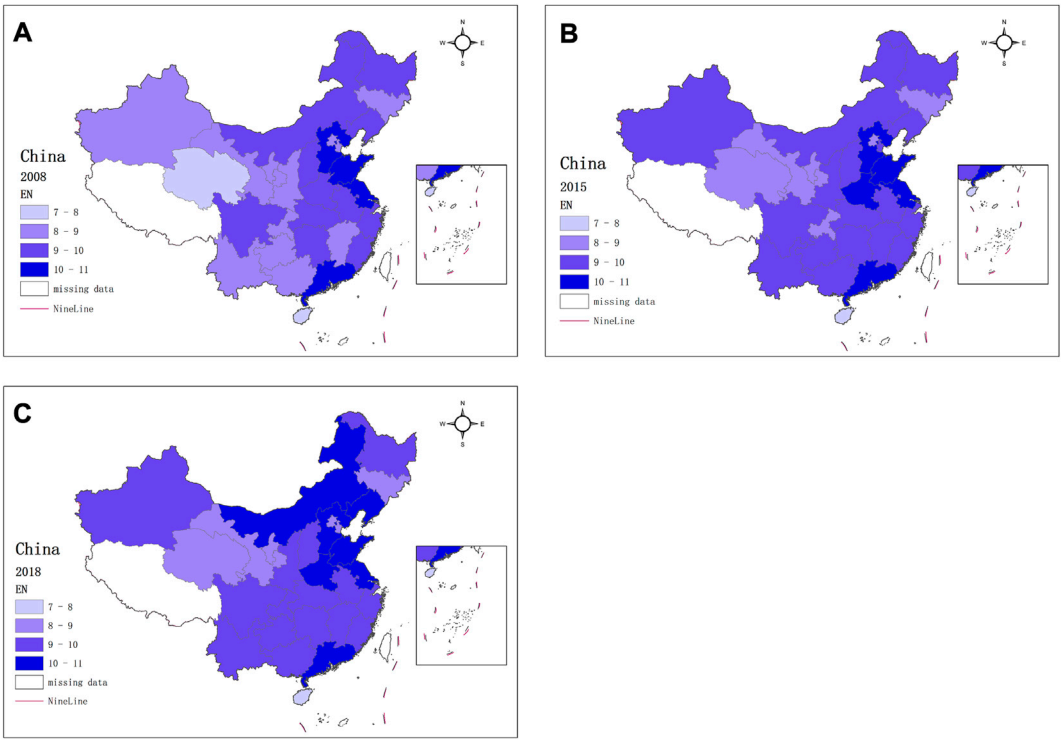

FIGURE 5
Spatial and temporal evolution of energy consumption.

3.3 Analysis of benchmark regression results

Green finance can promote high-quality economic development, mitigate environmental pollution, and reduce energy consumption (Figure 6). Among them, model (1) is the panel regression model between green finance and high-quality economic development. It is found that there is a positive correlation between green finance and high-quality economic development, that is, green finance can promote high-quality economic development. Model (2) is the panel regression model between green finance and environmental pollution. The results show that green finance and environmental pollution are significantly negatively correlated, which indicates that green finance can improve the ecological environment. The results of model (3) show that green finance has a significant negative impact on energy consumption, that is, green finance helps reduce energy consumption.

The positive impact of green finance on economic quality, environmental pollution, and energy consumption is significant (Figure 7). According to model (1) corresponding to graph (A) in Figure 7, it is found that after control variables are added, there is still a significant positive relationship between green finance and high-quality economic development. The results in graph (B) correspond to model (2). After controlling relevant variables, the relationship between green finance and environmental pollution is still negative, indicating that the improvement effect of green finance on environmental pollution is relatively significant. The results in graph (C) correspond to model (3), and it is also found that green finance has a significant negative impact on energy consumption. Among the control variables, the urbanization level and technological progress have a positive impact on high-quality economic development, and there is a significant negative correlation between government intervention and high-quality economic development. Economic growth can be promoted by the urbanization level through its impact on investment and consumption (Zhu and Huang, 2016). Meanwhile, the improvement in the urbanization level will promote coordinated development through investment and consumption so as to ultimately promote high-quality economic development. The improvement in the technological level will greatly promote the development of the innovation level and ultimately fuel the high-quality

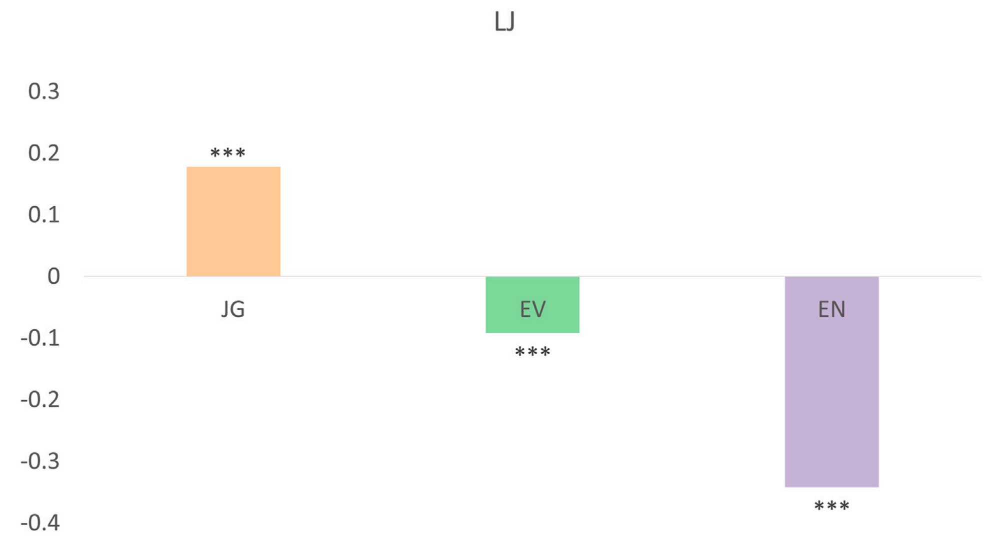

FIGURE 6
Benchmark regression results when control variables are not added (see Supplementary Table S4 for detailed results).

economic development level. The level of government intervention should be in an appropriate range. Excessive government intervention will affect the efficiency of resource allocation and be detrimental to high-quality economic development. The industrial structure has a significant negative impact on environmental pollution. If the industrial structure is adjusted and optimized, the energy utilization effect will be improved, thus reducing environmental pollution. In addition, technological progress, government intervention, and resident income have significant positive effects on energy consumption.

In 2021, the People's Bank of China issued the Report on the Development of Green Finance in China (2020), which pointed out that new progress has been made in the development of green finance, institutional arrangements have been continuously improved, and the basic practice has produced a marked effect. The vice president of the People's Bank of China said that China initially formed a policy system and market environment to support the development of green finance. In the new era, guiding high-quality economic development and reducing environmental pollution and energy consumption are important tasks for China's comprehensive and coordinated development. At the same time, we find that green finance has a significantly positive impact on high-quality economic development and reduces environmental pollution and energy consumption, indicating that we can promote China's comprehensive and coordinated development by boosting green finance development.

3.4 Heterogeneity analysis

In recent years, great importance has been attached to the development of the green economy both at home and abroad. China proposed to carry out the reform of the ecological civilization system and encouraged financial institutions to integrate green responsibility with the development of finance as much as possible in the process of operation. However, the development level of green finance in different regions of China is quite different. After green finance is explicitly proposed, the development of green finance in some regions is faster. Therefore, it is inferred that the impact of green finance in China on the economy, environment, and energy has spatial and temporal heterogeneity.

First, it is about spatial heterogeneity analysis.

In the eastern region, green finance can significantly promote high-quality economic development and reduce energy consumption; in the central region, the improvement of environmental pollution is very significant; in the western region, its impact on high-quality economy, environmental pollution, and energy consumption is not significant (Figure 8). From this, it can be inferred that the industrial structure in the eastern region has been optimized and upgraded, the production cost of enterprises has been relatively reduced, and the efficiency of technology research and development has been improved. Therefore, capital, manpower, and technology investment have gradually produced a positive net effect, and the energy utilization efficiency has significantly improved; thus, the environmental

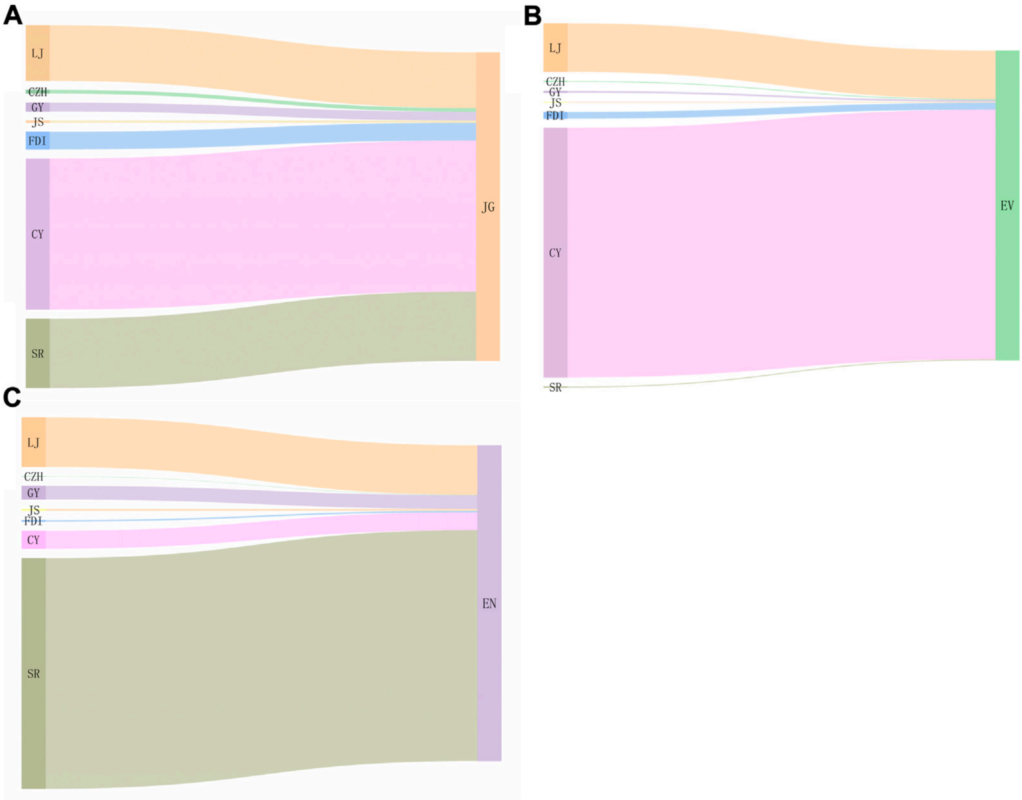

FIGURE 7
Impact of green finance on high-quality economic development, environmental pollution, and energy consumption after adding control variables (see Supplementary Table S5 for detailed results).

pollution situation is effectively improved. Therefore, the development of green finance does not play a significant role in improving the environment in the eastern region. In the central region, green finance can significantly mitigate environmental pollution. But the impact of green finance on high-quality economic development and energy consumption is not significant. However, in the western region, green finance can neither significantly promote high-quality economic development and reduce energy consumption nor significantly mitigate environmental pollution. It can be inferred from this result that, on one hand, compared with the eastern and central regions, the western region has uneven resource distribution, a relatively backward technological level, a relatively deteriorated industrial structure, and a large demand for energy. Therefore, the development of green finance, on the contrary, presents a trend of inhibiting the coordinated development and opening level of the western region, and ultimately shows a negative correlation with the high quality of the economy. The negative impact of green finance on energy consumption is not significant. On the other hand, the base number of carbon emissions, PM2.5 concentration, and industrial dust emissions in the western region is lower than that in the eastern and central regions, that is, the environmental pollution situation in the western region is better than that in the other two regions. The impact of green finance on the environment cannot be fully demonstrated, so the impact of green finance on the environment is not significant.

Second, it is about temporal heterogeneity.

After the clear proposal of green finance, the role of green finance in promoting a high-quality economy has increased, and the role of green finance in improving environmental pollution and energy consumption has decreased (Figure 8). Before green finance was clearly proposed, the impact of green finance on economic quality and environmental pollution was not significant, and the impact on energy consumption was very significant. After green finance is put forward, its impact on the high-quality economy, environmental pollution, and energy consumption has become insignificant. The coefficient value of the high-quality economy has significantly increased, and the absolute value of the coefficient of environmental pollution and energy consumption has decreased.

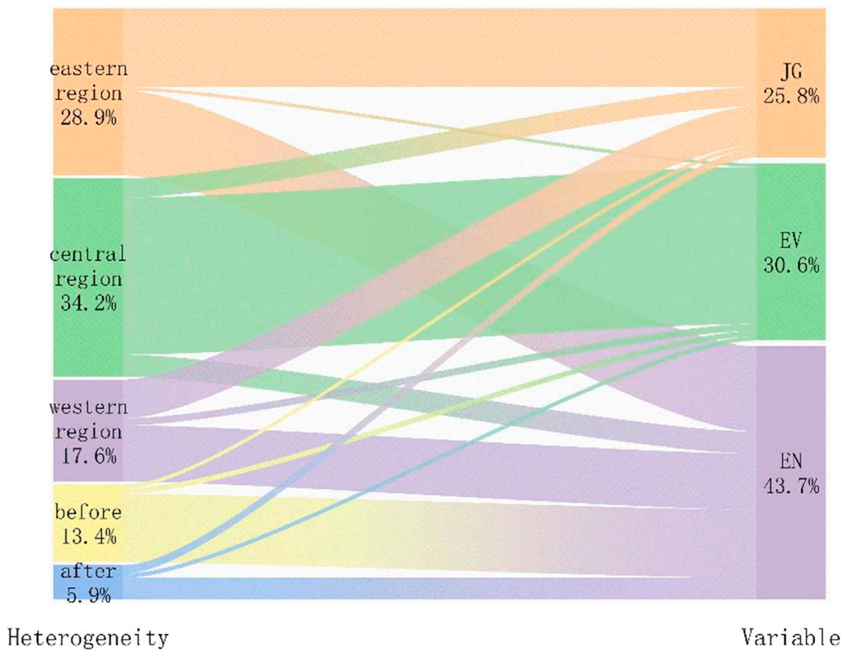

FIGURE 8
Impact of green finance on the spatial and temporal heterogeneity of high-quality economic development, environmental pollution, and energy consumption, and the impact on different regions of China and the impact of green finance before and after its proposition. Considering the differences in the economic level and resource allocation among eastern, central, and western regions of China, as well as the differences between different provinces and cities in the descriptive statistical results, the sample size is divided into three groups: the eastern, central, and western regions for regression again. The regression results show that the impact of green finance on the economy, environment, and energy is heterogeneous in the eastern, central, and western regions (see Supplementary Table S6 for detailed results). Green finance was clearly proposed for the first time in 2015. Therefore, the sample size was divided into two stages, 2008–2014 and 2015–2018, for research (see Supplementary Table S7 for detailed results).

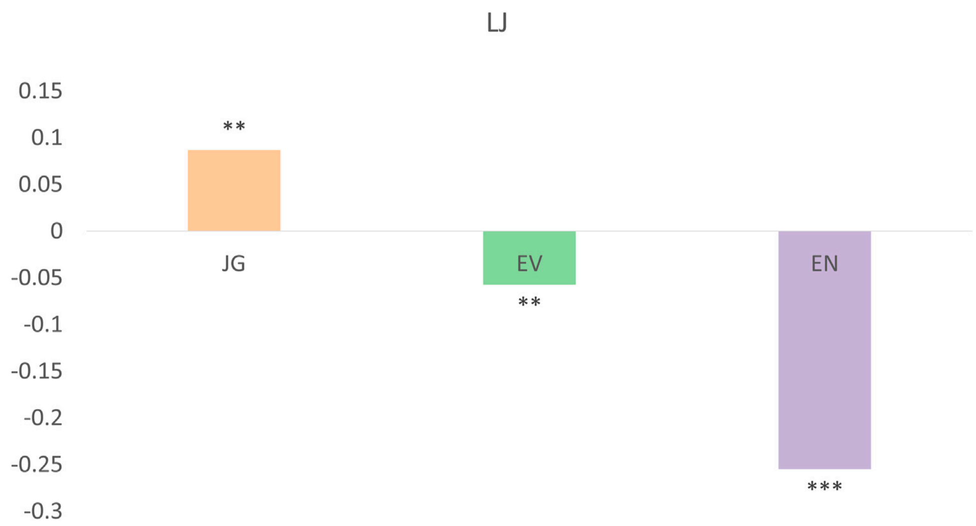

FIGURE 9
Stability test of green finance's impacts on high-quality economic development, environmental pollution, and energy consumption (see Supplementary Table S8 for detailed results). *, **, and *** mean significance at the significance level of 10%, 5%, and 1%, respectively.

3.5 Robustness test

Green finance has a relatively robust impact on high-quality economic development, environmental pollution, and energy consumption, indicating that the research results of this study are relatively reliable (Figure 9). This study adopts the method of changing the model to test the robustness. The maximum likelihood estimation method is selected to test the impact relationship between green finance, high-quality economic development, environmental pollution, and energy consumption. By observing the results in Figure 9, it is found that green finance has a significant impact on the economy, environment, and energy, and all coefficient values have passed the significance level at 5%.

4 Discussion

Understanding the impact of green finance on the economy, environment, and energy is crucial to sustainable development in the future and can help us cope with the financing challenges brought by climate change (Shunsuke et al., 2022). The authors have built high-quality economic development indicators from the five dimensions, namely, innovation, coordination, green, openness, and sharing, and have measured the development level of green finance based on the indicators of green credit, green securities, green investment, green insurance, and carbon finance. A relatively comprehensive evaluation method has been adopted to examine the impact of green finance on the economy, environment, and energy, which is conducive to promoting the development of green finance in many aspects and systematically promotes sustainable development, and we try to provide better practical solutions.

It is found that green finance has a significant positive effect on high-quality economic development, environmental pollution, and energy consumption (Figure 6 and Figure 7). Therefore, promoting the sustainable development of green finance, to a certain extent, is promoting high-quality economic development and reducing environmental pollution and energy consumption, which is fully consistent with the green low-carbon concept and the strategy of "carbon peak emissions and carbon neutrality" that we advocate. When the green growth strategy is applied in reality, it can not only reflect the economic achievements but can also affect the ecosystem (Onil et al., 2020). In particular, in the global context of vigorously developing digital technology, it can promote financial reform and the development of green fund project financing, and solve some technological problems in environmental resources (Karsten and Marian, 2021).

This study proposes that the positive effects of green finance on high-quality economic development, environmental pollution, and energy consumption have spatial and temporal heterogeneity, and the development strategy of green finance should be better formulated, according to the characteristics of space–time differences. In the eastern region, the positive effect on high-quality economic development and energy consumption is significant; in the central region, the positive effect on environmental pollution is significant; but in the western region, the effect on high-quality economic development, environmental pollution, and energy consumption is insignificant and even shows a negative effect on high-quality economic development. The huge regional differences explain the complexity of the development of green finance in different regions, which cannot be explained simply based on the law that the development of the financial industry decreases from east to west. From the perspective of promoting high-quality economic development, green finance is currently more suitable to be developed in the eastern region to give full play to its positive role. However, the financial foundation and resource endowment of the central and western regions are not as good as those of the eastern region. In particular, the massive loss of human capital is not conducive to the development of green finance in the central and western regions, and it is also difficult to promote high-quality economic development. Based on the situation of environmental pollution, green finance has more development edges in the central region. On one hand, the eastern region has a large population and a high degree of urbanization, which has a large intensity of environmental pollution. On the other hand, industrial development in the western region is slow, and the environmental damage rate and the environmental pollution intensity are also low. In general, the environmental pollution intensity in the central region can play a positive role in green finance. In addition, improving energy consumption is similar to but different from promoting high-quality economic development. The similar thing is the restriction of resource endowment, which makes energy consumption in the central and western regions unable to be significantly improved through green finance. The difference is that the adjustment and transfer of the industrial structure enable the eastern region to significantly reduce energy consumption while developing green finance. Before green finance was clearly proposed, its positive impact on energy consumption was very significant; after the introduction of green finance, its boosting effect on the high-quality economy has increased, but its positive impact on environmental pollution and energy consumption has decreased. It can be seen that the positive impact of green finance on the high-quality economy is persistent.

5 Conclusion and policy implications

This study uses the annual data on 30 provinces and cities in China from 2008 to 2018 to test the impact and heterogeneity of green finance on high-quality economic development, environmental pollution, and energy consumption through the panel regression model and have passed the robustness test. Through empirical analysis, the following conclusions are drawn: (1) green finance can significantly promote high-quality economic development, mitigate environmental pollution, and reduce energy consumption, and this conclusion is stable. (2) The impact of green finance on the economic high-quality level, environmental pollution, and energy consumption in different regions and at different times is heterogeneous. In the eastern region, green finance has a significant impact on high-quality economic development and energy consumption but not on environmental pollution; in the central region, green finance has a significant effect on improving environmental pollution; however, in the western region, green finance can neither significantly promote high-quality economic development nor significantly reduce environmental pollution and energy consumption. After the clear proposal of green finance, the role of green finance in promoting a high-quality economy has increased, and its positive impact on reducing environmental pollution and energy consumption has decreased. This study proposes that green finance has a systematic impact and spatial and temporal heterogeneity on high-quality economic development, environmental pollution, and energy consumption, which reflects the problems in the development of green finance in most countries and provides development ideas to solve the problems.

Based on the research conclusions, we make the following policy implications:

1) Under the policy background of promoting high-quality economic development and energy conservation and emission reduction, the local government can appropriately develop green finance on the basis of considering the allocation of resources of all parties and continue to improve the market system and legal system of green finance.
2) On one hand, we should continue to encourage the innovation of green financial products including the innovation of green products by enterprises and the innovation of financial products and financial services by financial institutions so as to promote the improvement of economic quality. On the other hand, we should build and improve the green governance system, focus on solving the pain points and difficulties in environmental development, improve the ecological environment, and promote sustainable development. In addition, we should enhance the synergy among the participants of green finance, pay attention to the inclusive effect of green achievements, publicize the green life concept to the masses, guide the change of a green way of life, and reduce energy consumption.
3) The long-term boosting effect of green finance on economic quality should be maximized. The western region should pay attention to the optimization and adjustment of the industrial structure and strive to solve the problems of uncoordinated development in all aspects. As most of the western regions are provinces rich in energy, they are highly dependent on energy. Therefore, we should devote ourselves to technological innovation and the implementation of green environmental protection projects in order to change the current energy consumption structure and improve the energy utilization efficiency. The central region should continue to learn from the eastern regions' advanced green governance methods, promote high-quality economic development through green governance, and promote the coordinated development of the economy, environment, and energy. The eastern region should make the best use of its own talent and resource advantages, strive to highlight its optimal value through green innovation, and promote high-quality economic achievements to be shared by more people.

Data availability statement

Publicly available datasets were analyzed in this study. These data can be found at: the Yearbook of Science and Technology of China, the China Statistics Yearbook, the Yearbook of Environmental Statistics of China, the Yearbook of Chinese Industry Statistics, the Fourth National Economic Census, the China Carbon Accounting Databases (CEADs), Guotai'an CSMAR Databases, the Ministry of Science and Technology of China, the Ministry of Environmental Protection of China, the National Bureau of Statistics of China, and the statistical yearbooks of various provinces.

Author contributions

CL: conceptualization, funding acquisition, writing—review and editing, and supervision. ZC: data curation, methodology, visualization, writing—original draft, and formal analysis. YW: writing—review and editing and supervision. XZ: data curation and writing—original draft. HJ: data curation. YX: writing—review and editing. BZ: writing—review and editing. GZ: writing—review and editing. YW: writing—review and editing.

Funding

This research was supported by the Hebei Social Science Foundation Project (No: HB18YJ011) and the 2020 University Level Scientific Research Fund Project of Guizhou University of Finance and Economics (No: 2020XZD01).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.1032586/full#supplementary-material

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frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 11 November 2022
DOI 10.3389/fenvs.2022.1036482

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OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Environmental Economics and Management, a section of the journal Frontiers in Environmental Science

RECEIVED 04 September 2022
ACCEPTED 18 October 2022
PUBLISHED 11 November 2022

CITATION
Wang B, Yang M and Zhang X (2022), The effect of the carbon emission trading scheme on a firm's total factor productivity: An analysis of corporate green innovation and resource allocation efficiency.
Front. Environ. Sci. 10:1036482.
doi: 10.3389/fenvs.2022.1036482

The effect of the carbon emission trading scheme on a firm's total factor productivity: An analysis of corporate green innovation and resource allocation efficiency

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This study investigates the effect of the carbon emission trading scheme on a firm's total factor productivity in China. With a sample from 2008 to 2019, applying the time-varying DID method, our empirical results reveal that the carbon emission trading scheme significantly improves a firm's total factor productivity, which provides evidence for Porter's hypothesis. Moreover, there are two channels through which the total factor productivity is impacted: the corporate green innovation channel and the resource allocation efficiency channel. Furthermore, the impact of the carbon emission trading scheme is more pronounced for private firms, and firms in the provinces with higher institutional development, lower environmental quality, and greater law enforcement of environmental protection tend to have larger total factor productivity. Our models survive numerous robustness checks.

KEYWORDS

carbon emission trading scheme, total factor productivity, green innovation, resource allocation efficiency, time-varying DID method

1 Introduction

Nowadays, global warming is one of the biggest challenges all around the world, and it is highly correlated with the development of the global economy. After the implementation of the Tokyo Protocol, with the market mechanism, the concept of carbon emission reduction has developed sustainably, and the carbon emission trading scheme (ETS) has become extremely crucial for countries to control the carbon emission (Anderson and Di Maria, 2011; Lin and Jia, 2019; Hu et al., 2020). The European Union Emissions Trading Scheme (EUETS) is the most mature market for carbon emission, which not only encourages emission reduction of firms but also helps Europe transform into a low-carbon economy (Betz et al., 2006; Twomey et al., 2012).

As the biggest country of carbon emission in the world, China's carbon emission achieved 10 billion tons in 2018, which accounted for 28% of the global carbon emission. At an early stage, China's environmental regulation mainly consists of command-and-control; however, the effect on emission reduction is weak, and the cost is high and unsustainable (Tang et al., 2020a; Cai and Ye, 2020). Under the pressure of emission reduction, China tends to explore the market-based mechanism to reduce carbon emission. Compared with developed countries, the start of ETS in China is relatively late, but the development of ETS is relatively rapid. On 16th July 2021, the nation-wide ETS formally started, with 2,162 firms in the electric power industry being included in this system, which covers approximately 4.5 billion tons of carbon emission. The Chinese ETS has become the biggest carbon market in the world. China's ETS pilot started in 2013 in seven provinces, namely, Shenzhen, Beijing, Shanghai, Guangdong, Tianjin, Hubei, and Chongqing; eight industries are involved: petrochemicals, paper, construction, electric power, chemical industry, nonferrous metal mining, metals, and air transport.

Numerous studies investigated the impact of the ETS in China, including air pollution reduction (Yan et al., 2020), electricity regulation (Zeng et al., 2018), fixed asset changes (Dong et al., 2022), carbon allowance allocation (Jin et al., 2020), carbon leakage (Yu et al., 2021), economic growth with low carbon transformation (Fan et al., 2016; Wang et al., 2019; Zhu et al., 2020), and regional carbon equality (Zhang S. et al., 2021). However, the impact of the ETS in China on a firm's total factor productivity (TFP) has been ignored in the current literature, which is vital for the economic growth in the long run (Krugman, 1995). In recent years, the sustainable growth of China's economy relies more and more on the improvement of productivity instead of the accumulation of inputs, which forces firms to accelerate the productivity (Islam et al., 2005; Jin et al., 2018). Thus, it is substantially important to explore the impact factor of a firm's productivity, and China is experiencing a low-carbon transformation; thus, understanding the impact of emission reduction is crucial for China's economic growth. As a result, taking the ETS as a quasi-natural experiment, this study attempts to investigate the impact of emission reduction in China on a firm's TFP.

With a sample from 2008 to 2019, applying the time-varying DID method, our empirical results reveal that the carbon emission trading scheme significantly improves a firm's total factor productivity, which provides evidence for Porter's hypothesis. Moreover, there are two channels through which the total factor productivity is impacted: the corporate green innovation channel and the resource allocation efficiency channel. Furthermore, the impact of the carbon emission trading scheme is more pronounced for private firms, and firms in provinces with higher institutional development, lower environmental quality, and greater law enforcement of environmental protection tend to have larger total factor productivity.

This study contributes to current studies in the following aspects: first, we investigate the impact of ETS on TFP. Xiao et al. (2021) also studied their relationship, but our research focuses on corporate green innovation and resource allocation efficiency channels which were not examined in previous studies. Second, from the perspective of the econometric method, most studies concerning the ETS apply the DID approach (Xiao et al., 2021; Zhang and Wang, 2021; Sun et al., 2022), and these studies consider 2013 as the year of policy implementation. However, in reality, the year of policy implementation differs across different provinces; thus, this study uses time-varying DID to identify the impact of the ETS. Finally, the heterogeneity is considered. Xiao et al. (2021) investigated industrial heterogeneity, and we extend their research by examining the heterogeneity of corporate ownership and provincial difference.

The remainder of this study is organized as follows. Section 2 provides a brief review of the literature. Section 3 describes the research design. Section 4 analyzes the empirical results. Section 5 provides the robustness checks of our model. Finally, Section 6 concludes the study.

2 Literature review and hypothesis development

2.1 Literature review

The studies on the ETS have attracted a lot of academic attention; however, no consensus has been achieved. Some researchers show that the emission reduction conducted by environmental regulation not only increases corporate costs but also crowds out other production and profitable investment. Then, the emission reduction will eventually harm corporate profit (Jorgenson and Wilcoxen, 1990; Jaffe et al., 1995). Based on the data on the energy department in Germany, Rogge et al. (2011) found that the EUETS does not provide enough incentives for firms to innovate. Feng et al. (2017) also showed that the ETS significantly impedes corporate innovation, especially for firms in the non-environmental industry.

Opposite opinions are also found in the current literature. Porter and Vander Linde (1995) claimed that environmental regulation can stimulate corporate innovation, and this is also referred to as Porter's hypothesis. Calel and Antoine Dechezleprêtre (2012) found that a firm's green innovation improves by 10% due to the EUETS, and other patents are not crowded out. The same results are found in Ireland and China (Anderson et al., 2010; Lv and Bai, 2021). From the perspective of financial performance, Jarait and Maria (2016) proved that the profit is not affected by the EUETS, and the economic performance of German manufacturers has been improved (Lschel et al., 2018). Moreover, numerous studies have shown that the EUETS does not have a negative impact on a firm's competitiveness (Demailly and Quirion, 2008; Joltreau and Sommerfeld, 2016). Lutz (2016) claimed that the EUETS is positively associated with TFP in Germany.

Numerous studies have investigated the impact of the ETS in China. Some findings show that a firm's competitiveness, corporate excess return, and corporate performance are positively correlated with the ETS (Wen et al., 2020; Luo et al., 2021; Sun et al., 2022). Peng et al. (2021) found that the SO_2 emissions trading pilot has a positive impact on a firm's TFP. Xiao et al. (2021) found that the ETS can significantly improve TFP, and firm's operating channel and the profitability capacity channel are investigated. Zhang Y. et al. (2022) showed that the ETS significantly improves the green development efficiency and regional carbon equality. Yu et al. (2021) found that the ETS has accelerated both the depth and breadth of outward direct investment from China.

2.2 Hypothesis development

Environmental problems exhibit negative externality, and regulation is needed for environmental governance to internalize the cost of externality. Dales (1968) proposed a public policy relating to pollution by using a market-based mechanism, which can adjust the negative externality of pollution. The market-based price system has more advantages in terms of lower pollution reduction cost and higher efficiency (Montgomery, 1972; Albrizio et al., 2017).

The ETS can improve a firm's TFP in three aspects. First, from the perspective of cost, the ETS will stimulate firms to lower long-term emission costs in terms of low carbon technology transformation and higher resource utilization efficiency (Anderson et al., 2010; Feng et al., 2020). Traditional environmental regulation increases a firm's production cost, and those policies rarely provide incentives for firms to innovate; thus, the regulation cost of firms cannot be cancelled out by corporate innovation, which, in turn, reduces the firm's productivity (Tang et al., 2020b; Cai and Ye, 2020). On the contrary, the market-based ETS provides more flexibility, and firms can choose the amount of carbon emission by comparing the marginal cost of emission reduction and the carbon price, which significantly reduces the cost of regulation (Albrizio et al., 2017; Feng et al., 2020). Schmalensee and Stavins (2013) found that the regulation cost of the SO_2 emissions trading pilot decreases by 15%–90% compared to traditional regulation policies.

Second, from the perspective of benefit, the establishment of the ETS has a positive impact on a firm's income. First, firms with low carbon emission can benefit from selling their carbon emission quota. Second, firms are willing to invest more in green innovation due to the ETS, and this makes firms produce more green products and have higher environmental responsibilities, which causes two consequences. The first one is that the firm's green products will have a higher value-added benefit and more consumers, which increases sales and profit (Xiao et al., 2021). The second one is that higher environmental responsibilities will attract more investors, which increases the firm's market value (Wen et al., 2019; Zhang S. et al., 2021). Finally, governments provide more subsidies for firms participating in the ETS to encourage them in emission reduction, which significantly reduces the firm's cost.

Finally, from the perspective of operational efficiency, the ETS will lead firms to make adjustments to their production and management (Luo et al., 2021). On one hand, the ETS stimulates firms to transform their way of production, and they tend to produce innovative products with low energy consumption, which, in turn, increases the TFP and the final production (Lutz, 2016). On the other hand, the ETS will lead firms to invest more in the capital with higher energy efficiency and reduce the investment in energy and labor force, which increases the total productivity.

Based on the aforementioned arguments, we propose the following hypothesis:

Hypothesis 1. ETS will improve a firm's TFP.

3 Research design

3.1 Sample selection

This study selects listed firms from the Chinese stock market in the following industries: petrochemicals, paper, construction, electric power, nonferrous metal mining, metals, and air transport. The data on the firm's green patents are obtained from the State Intellectual Property Office, and the other data are extracted from the China Stock Market and Accounting Research (CSMAR) database. Moreover, we excluded those firms marked ST and PT. Our final sample contains 652 firms and 4,394 observations, our dataset is unbalanced due to missing values, and the data are winsorized at the 1% and 99% levels.

3.2 Dependent variable

Our dependent variable is the TFP, and to measure it, we start with the Cobb–Douglas production function, which is presented as follows:

$$Y_{it} = A_{it} L_{it}^{\alpha} K_{it}^{\beta}, \tag{1}$$

where Y denotes the output; L and K present the labor and the capital, respectively; and A is the productivity. We take the natural logarithm on both sides, and the following equation is obtained:

$$\ln Y_{it} = \alpha \ln L_{it} + \beta \ln K_{it} + u_{it}, \tag{2}$$

where u_{it} contains the information on the firm's TFP. The OP method and LP method are widely applied to measure the TFP in current studies. The OP method requires positive real investment, which results in missing observations (Olley and

TABLE 1 Year of implementation of the ETS for different provinces.

Province	Year of implementation of the ETS	First year of DID_{it} equals 1
Shenzhen	2013.06	2013
Shanghai	2013.11	
Beijing		
Guangdong	2013.12	2014
Tianjin		
Hubei	2014.04	
Chongqing	2014.06	

Pakes, 1996). Real investment is not used in the LP method; the input of intermediary goods is used instead; thus, missing observations are much less, and the endogeneity problem is also relieved (Levinsohn and Petrin, 2003). As a result, following Tang et al. (2020a) and Xiao et al. (2021), the LP method is applied in this study. Moreover, the firm's Y is measured by corporate sale; L is measured by cash paid to employees; compared with the number of employees, this measure can better reflect the cost of labor; K is the sum of fixed assets and intangible assets; the intermediary input is measured by cash used to purchase merchandise and labor. Following Eq. 2, the natural logarithm of residuals u_{it} is the firm's TFP (TFP_LP).

3.3 Independent variables

To identify the impact of the ETS, we construct a dummy variable DID_{it}, which is the product of time dummy and the dummy of the ETS. Thus, DID_{it} equals 1 if the province where firm i is located implements the ETS at year t; otherwise, it is 0. More specifically, if the ETS is implemented in the first half of the year in this province, then we consider this year as the first year of the ETS, and if the ETS is implemented in the second half of the year in this province, then next year will be considered as the first year of the ETS. Table 1 shows the year of implementation of the ETS.

TABLE 2 Definitions of the variables.

Variable	Definition
TFP_LP	TFP computed by the LP method
DID	Dummy variable of the product of the time dummy and the dummy of the ETS: it equals 1 if the province where firm i is located implements the ETS at year t; otherwise, it is 0
Size	Natural logarithm of total assets
Lev	Total liabilities divided by total assets
Growth	Growth rate of sales
TQ	Tobin's Q
ROA	Return on assets of firms
Age	Natural logarithm of the number of years since the incorporation of the firm
Top 10	Percentage of shares held by the top 10 shareholders

Based on the current studies, the following control variables are included in our model: firm size (Size), leverage ratio (Lev), corporate growth ability (Growth), Tobin's Q (TQ), return on assets (ROA), firm's age (Age), and equity concentration (Top 10). The detailed definition is given in Table 2. Moreover, industry- and year-fixed effects are controlled, and the interaction effect between the industry and year and the interaction effect between the province and year are also included.

3.4 Model specification

As we can see in Table 1, the implementation of the ETS differs across different provinces; thus, to better identify the impact of the ETS, the time-varying DID method is used in this study. Our model is specified as follows:

$$TFP\_LP_{it} = \beta_0 + \beta_1 DID_{it} + \sum \beta_i X_{it} + Year + Industry + Industry{*}Year + Regions{*}Year + \varepsilon_{it}, \quad (3)$$

where TFP_LP presents the firm's TFP computed by the LP method, DID denotes the impact of the ETS, X is the set of control variables, and ε shows the random errors. Both year- and industry-fixed effects are included, the interaction between the year and industry is also controlled, and the interaction between the province and year is included as well.

Table 3 shows the descriptive statistics, and it can be seen that the mean of TFP_LP is 12.04 with a standard deviation of 0.882. Then, the mean of DID is 0.158, which means that 15.8% of firms in our sample participate in the ETS.

4 Empirical results

4.1 The impact of the ETS on a firm's TFP

Table 4 shows the impact of the ETS on the TFP of firms; column 1 shows the impact of DID on TFP_LP without control variables, and all control variables are added in column 2. As we specified in Eq. 3, four other fixed effects are added as well.

Our empirical results show that the coefficients of DID in both columns are significantly positive, which means that the ETS and TFP_LP are positively correlated. The ETS can significantly improve the firm's TFP, which is in line with our expectations and coincides with the conclusion of Lutz (2016) and Xiao et al. (2021), and we provide evidence for Porter's hypothesis.

TABLE 3 Descriptive statistics of the variables.

	N	Mean	SD	Min	Max	Median
TFP_LP	4,394	12.04	0.882	7.831	14.67	11.97
DID	4,394	0.158	0.365	0	1	0
Size	4,394	22.49	1.374	19.66	26.41	22.31
Lev	4,394	0.495	0.205	0.056	0.997	0.504
Growth	4,394	0.155	0.390	-0.543	4.370	0.092
TQ	4,394	1.737	0.999	0.800	11.42	1.432
ROA	4,394	0.031	0.061	-0.353	0.339	0.029
Age	4,394	11.71	6.293	2	26	12
Top10	4,394	56.72	15.51	14.82	90.61	56.59

TABLE 4 Results of the impact of the ETS on a firm's TFP. Dependent variable: TFP_LP.

	(1)	(2)
DID	0.117***	0.092**
	(2.843)	(2.571)
Size		0.277***
		(8.955)
Lev		−0.055
		(−0.581)
Growth		0.187***
		(7.494)
TQ		−0.011
		(−0.933)
ROA		1.321***
		(7.824)
Age		0.118*
		(1.939)
Top 10		−0.002**
		(−2.142)
_cons	−30.835	−47.322
	(−0.890)	(−1.429)
Year	Yes	Yes
Ind	Yes	Yes
Ind*year	Yes	Yes
Province*year	Yes	Yes
N	4,394	4,394
Adj_R^2	0.252	0.469

Note: *** indicates significance at the 1% level, ** indicates significance at the 5% level, and * indicates significance at the 10% level. Standard errors are reported in parentheses.

In terms of control variables, the coefficient of SIZE is significantly positive; thus, larger firms tend to have higher TFP. The coefficients of Growth and ROA are also positive, which shows that firms with higher profitability are likely to have funds to finance corporate innovation; thus, they are more productive. Firms with a higher age tend to have greater productivity since they may be featured with better corporate governance, which further helps improve the TFP. The coefficient of Top 10 is negative; thus, a larger equity concentration reduces the firm's TFP.

TABLE 5 Dynamic effect of the ETS on a firm's TFP.

	(1)	(2)
$DID_{i,t-4}$	−0.072	−0.077
	(−1.141)	(−1.354)
$DID_{i,t-3}$	−0.084	−0.041
	(−1.564)	(−0.830)
$DID_{i,t-2}$	−0.057	−0.047
	(−1.254)	(−1.156)
$DID_{i,t-1}$	−0.043	−0.015
	(−1.358)	(−0.552)
$DID_{i,t+1}$	0.080**	0.065**
	(2.281)	(2.393)
$DID_{i,t+2}$	0.124**	0.115***
	(2.570)	(2.835)
$DID_{i,t+3}$	0.109*	0.139***
	(1.837)	(2.764)
$DID_{i,t+4}$	0.109*	0.125**
	(1.684)	(2.264)
_cons	−31.413	−47.983
	(−0.908)	(−1.459)
Control	No	Yes
Year	Yes	Yes
Ind	Yes	Yes
Ind*year	Yes	Yes
Province*year	Yes	Yes
N	4,394	4,394
Adj_R^2	0.254	0.470

Note: *** indicates significance at the 1% level, ** indicates significance at the 5% level, and * indicates significance at the 10% level. Standard errors are reported in parentheses.

4.2 Robustness of the baseline results

We conducted some sensitivity tests to check the robustness of our main findings.

4.2.1 Verifying the parallel trend assumption

To verify the parallel trend assumption, we conducted a dynamic DID analysis, and the results are presented in Table 5. Our findings show that the impact of the ETS is not significant for the 4 years before the implementation of the ETS, which claims that the TFP of both treatment and control firms does not differ before the ETS. In addition, the impact of the ETS is significantly positive for the 4 years after the implementation of the ETS, which means that the ETS improves the firm's TFP, and this improvement is maintained. Our results show that the parallel trend assumption is satisfied.

TABLE 6 Robustness of the baseline results.

	Alternative measures of variables		Counterfactual test	PSM-DID
	(1)	(2)	(3)	(4)
	TFP_OP	TFP_LP	TFP_LP	TFP_LP
DID	0.101***	0.081***	0.019	0.099***
	(2.830)	(2.631)	(0.444)	(2.878)
_cons	−22.778	−46.894	−46.802	−37.125
	(−0.563)	(−1.413)	(−1.401)	(−0.554)
Control	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
Ind	Yes	Yes	Yes	Yes
Ind*year	Yes	Yes	Yes	Yes
Province*year	Yes	Yes	Yes	Yes
N	4,394	4,394	4,394	2,941
Adj_R^2	0.290	0.469	0.467	0.496
ATT				1.91

Note: *** indicates significance at the 1% level, ** indicates significance at the 5% level, and * indicates significance at the 10% level. Standard errors are reported in parentheses.

4.2.2 Alternative measures of variables

First, we use the OP method to recompute the TFP. More specifically, capital expenditure is used to measure corporate investment. Empirical results are reported in column 1 of Table 6, the coefficient of DID is significantly positive, which is in line with the results of TFP_LP, and the ETS can significantly improve the firm's TFP.

Second, after the first seven provinces implemented the ETS, two other provinces also implemented the ETS in December 2016; thus, we added these two provinces to our baseline model. The results are reported in column 2 of Table 6, and the coefficient of DID is still significantly positive, which coincides with the results of Table 4.

4.2.3 Counterfactual test

We also conducted a counterfactual test. More specifically, we took the year of implementation of the ETS 3 years ahead, and the empirical results are presented in column 3 of Table 6. Industry- and year-fixed effects are controlled, and the interaction effect between the industry and year and the interaction effect between the region and year are also included.

From column 3 of Table 6, the coefficient of DID is positive but insignificant, which indicates that the impact of the ETS on the firm's TFP is statistically insignificant if the year of implementation of the ETS is 3 years ahead. This coincides with our expectation that the improvement of the firm's TFP is due to the implementation of the ETS.

4.2.4 Propensity score matching method

The characteristics of firms in the province with the ETS may differ from those in the province without the ETS. To overcome the sample selection problem, we used the propensity score matching (PSM) method to form a treatment group and a control group. The results are shown in column 4 of Table 6, where the ATT value is significant at a 10% level, and the coefficient of DID is significantly positive; thus, the PSM-DID method also provides the same result that the ETS significantly improves the TFP.

5 Mechanism analysis

Our findings show that the ETS can significantly improve a firm's TFP, and these findings survive numerous robustness checks. This section will further investigate the channels through which the TFP is impacted.

5.1 Corporate green innovation

As Porter's hypothesis states, environmental regulation can stimulate corporate innovation, and it will reduce the cost of firms by energy saving and quality improvement, which will further improve corporate competitiveness (Porter and VanderLinde, 1995). The ETS internalize the environmental externality into the firm's cost. Thus, to save the quota of carbon emission, firms tend to innovate for emission and production cost reduction. Thus, corporate green innovation will increase (Feng et al., 2020). Meanwhile, the government will provide sustainably dynamic economic incentives (Perman et al., 2011), and firms with green innovation may sell quotas for extra benefits, which, in turn, stimulates the R&D in green technology (Feng et al., 2020). Moreover, the ETS is a market-based environmental regulation, and involved firms can easily obtain information on green technology. This largely decreases the risk of corporate innovation, and it also helps firms apply green innovation into production practice; thus, the ability of corporate green innovation will be enhanced (Feng et al., 2020). As a result, corporate green innovation has a mediation effect between the ETS and the firm's TFP.

To measure corporate green innovation, we used the green patents (patent) applied by listed firms. Following Sobel (1982) and Baron and Kenny (1986), the three-step regression procedure was used, and the following regressions were estimated:

$$Patent_{it} = \beta_0 + \beta_1 DID_{it} + \sum \beta_i X_{it} + Year + Industry + Industry{*}Year + Regions{*}Year + \varepsilon_{it}, \quad (4)$$

$$TFP\_LP_{it} = \beta_0 + \beta_1 DID_{it} + \beta_2 Patent_{it} + \sum \beta_i X_{it} + Year + Industry + Industry{*}Year + Regions{*}Year + \varepsilon_{it}. \quad (5)$$

Empirical results are reported in columns 1 and 2 of Table 7. Column 1 shows that the coefficient of DID is 0.145 with a significance level of 10%, which reveals that the green patents increase by 14.5% after the ETS. Our findings are consistent with those of Anderson et al. (2010) and Lv and Bai (2021). Column 2 shows that the coefficients of the patent and DID are both significantly positive; thus, green innovation has a partial mediation effect. In addition, the Sobel test also proves that the mediation effect of the patent is significant.

5.2 Resource allocation efficiency

The ETS will lead technology and fund low-carbon firms. Then, the quota of carbon emission will flow from firms with high pollution to firms with low pollution, and production factors will flow from less-productive firms to more-productive firms; thus, firms with high productivity will obtain more production resources. Moreover, firms with high emission will face high environmental costs under the ETS, and considering emission reduction cost and economic profit, firms will tend to reallocate the production factors, and they will invest more in sectors with clean technology and high efficiency (Brandt and Biesebroeck, 2009; Klenow and Hsieh, 2009), which will further improve the TFP of firms (Feng et al., 2020).

We applied the investment efficiency proposed by Richardson (2006) to measure the resource allocation efficiency. The investment efficiency is defined as the difference between the actual investment level and the expected investment level of firms, which is estimated as follows:

$$Inv_{i,t} = \beta_0 + \beta_1 Growth_{i,t-1} + \beta_2 Size_{i,t-1} + \beta_3 Lev_{i,t-1} + \beta_4 Cash_{i,t-1} + \beta_5 Age_{i,t-1} + \beta_6 R_{i,t-1} + \beta_7 Invest_{i,t-1} + \varepsilon_{i,t}, \quad (6)$$

where *Inv* is calculated as the ratio of gross capital expenditure to total assets. *Growth* denotes Tobin's Q. *Size* is defined as the natural logarithm of total assets. *Lev* represents the leverage of firms. *Cash* is the operational cash flow scaled by total assets. *Age* is defined as the natural logarithm of the listed years. *R* represents the annual return of stock prices. Residuals indicate the extent to which the firm deviates from the optimal investment; in this study, the absolute value of residuals is used to measure the investment efficiency (Efficiency). More specifically, higher efficiency indicates lower investment efficiency.

Following Sobel (1982) and Baron and Kenny (1986), the three-step regression procedure was used, and the following regressions were estimated:

$$Efficiency_{it} = \beta_0 + \beta_1 DID_{it} + \sum \beta_i X_{it} + Year + Industry + Industry{*}Year + Regions{*}Year + \varepsilon_{it}, \quad (7)$$

$$TFP\_LP_{it} = \beta_0 + \beta_1 DID_{it} + \beta_2 Efficiency_{it} + \sum \beta_i X_{it} + Year + Industry + Industry{*}Year + Regions{*}Year + \varepsilon_{it}. \quad (8)$$

Empirical results are reported in columns 3 and 4 of Table 7. Column 3 shows that the coefficient of DID is negative but insignificant. Column 4 shows that the coefficients of efficiency and DID are both significant. Moreover, the Z-statistics of the Sobel test is greater than 0.97, which proves that the mediation effect of efficiency is significant.

6 Heterogeneity analysis

This section will further investigate the heterogeneity in terms of corporate ownership and provincial difference.

6.1 Corporate ownership

In the Chinese stock market, there are numerous state-owned companies (SOEs), and compared with private firms, their reaction to the ETS differs. First, SOEs undertake social and political burdens; thus, they are less sensitive and less active in facing environmental regulations and innovation incentives (Peng et al., 2021). Second, SOEs are less motivated to improve the efficiency; thus, it is more difficult for them to reform. Thus, the impact of the ETS will be more pronounced for private firms. Empirical results are presented in columns 1 and 2 of Table 9. Our findings show that the impact of the ETS is

TABLE 7 Regression results for the corporate green innovation channel and the resource allocation efficiency channel.

	Corporate green innovation		Resource allocation efficiency	
	(1)	(2)	(3)	(4)
	Patent	TFP_LP	Efficiency	TFP_LP
DID	0.145*	0.089**	−0.002	0.091**
	(1.771)	(2.494)	(−0.246)	(2.575)
Patent		0.016*		
		(1.811)		
Efficiency				−0.317***
				(−4.274)
_cons	−43.224	−46.615	9.440**	−44.326
	(−1.390)	(−1.412)	(2.195)	(−1.327)
Control	Y	Y	Y	Y
Year	Y	Y	Y	Y
Ind	Y	Y	Y	Y
Ind*year	Y	Y	Y	Y
Province*year	Y	Y	Y	Y
N	4,394	4,394	4,394	4,394
Adj_R^2	0.051	0.487	0.026	0.467
Sobel	Z = 1.367 > 0.97	Z = 1.775 > 0.97		

Note: *** indicates significance at the 1% level, ** indicates significance at the 5% level, and * indicates significance at the 10% level. Standard errors are reported in parentheses.

significantly positive for private firms, whereas it is insignificant for SOEs.

6.2 Provincial difference

6.2.1 Institutional development

The impact of the ETS is highly correlated with the provincial development of institutions. When institutions are more developed, the ETS will also be more market-oriented, and transaction cost due to information asymmetry will decrease; thus, the efficiency of transactions will be greater. To measure institutional development, following Zhang et al. (2022), we used the National Economic Research Institute (NERI) marketization index proposed by Wang et al. (2018). Furthermore, we split the sample into two subsamples, one containing provinces whose NERI index is greater than the mean of the NERI index for all provinces and the other one containing provinces whose NERI index is lower than their mean value. Empirical results are presented in columns 3 and 4 of Table 9. The impact of the ETS is significantly positive in the subsample with a higher NERI index; however, this impact is insignificant in the subsample with a lower NERI index. Thus, the impact of the ETS is greater in provinces with higher institutional development.

6.2.2 Provincial environmental quality

Provincial environmental quality has a great impact on the policy effect of the ETS. In the provinces with low environmental quality and high pollution, the enforcement of environmental regulation is much higher, and the environmental cost of firms is larger. Thus, firms in these provinces are more motivated by green technology and green production. As a result, the impact of the ETS will be more pronounced for provinces with lower environmental quality. To measure the environmental quality, we used the CO_2 emission per person of each province from 2008 to 2012. More specifically, provinces whose CO_2 emission is above the median are classified as provinces with low environmental quality; otherwise, they are provinces with high

TABLE 8 Classification of provinces with environmental quality.

Low environmental quality	High environmental quality
Hebei, Heilongjiang, Jilin, Jiangsu, Liaoning, Neimenggu, Ningxia, Qinghai, Shandong, Shanxi, Shaanxi, Shanghai, Tianjin, Xinjiang, and Zhejiang	Anhui, Beijing, Fujian, Gansu, Guangdong, Guangxi, Guizhou, Hainan, Henan, Hubei, Hunan, Jiangxi, Sichuan, Yunnan, and Chongqing

TABLE 9 Heterogeneity analysis.

	SOE	Private	High institutional development	Low institutional development	High environmental quality	Low environmental quality	High environmental regulation	Low environmentalregulation
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
DID	0.058	0.096*	0.091**	−0.011	0.143**	0.026	0.075*	0.015
	(1.303)	(1.739)	(2.126)	(-0.146)	(2.154)	(0.639)	(1.704)	(0.232)
_cons	−23.258	159.503*	−79.671**	16.225	15.775	−100.123***	−52.856	36.796
	(−0.636)	(1.964)	(−2.196)	(0.216)	(0.256)	(−2.596)	(−1.517)	(0.572)
Control	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Ind	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Ind*year	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Province*year	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	2,498	1862	2058	2,336	2,163	2,226	3,134	1,260
Adj_R^2	0.468	0.562	0.471	0.473	0.445	0.509	0.478	0.470

Note: *** indicates significance at the 1% level, ** indicates significance at the 5% level, and * indicates significance at the 10% level. Standard errors are reported in parentheses.

10.3389/fenvs.2022.1036482

environmental quality. Precise provinces are detailed in Table 8. Empirical results are reported in columns 5 and 6 of Table 9. The impact of the ETS is significantly positive in provinces with low environmental quality and insignificant in provinces with high environmental quality.

6.2.3 Enforcement of environmental regulation

The enforcement of environmental regulation maintains the function of the ETS. Enhanced enforcement of environmental regulation increases the cost of breaking laws, and then, it decreases the likelihood of exerting illegal emission for firms; thus, the system of the ETS can be well implemented. We used the number of environmental punishments to measure the enforcement of environmental regulation. The data were collected from the China Environment Yearbook. Furthermore, we split the sample into two subsamples, one containing provinces whose number of environmental punishments is greater than the mean of environmental punishments for all provinces and the other one containing provinces whose number of environmental punishments is lower than their mean value. Empirical results are presented in columns 7 and 8 of Table 9. The impact of the ETS is significantly positive in the subsample with more environmental punishments; however, this impact is insignificant in the subsample with fewer environmental punishments. Thus, the impact of the ETS is greater in provinces with higher enforcement of environmental regulation.

7 Conclusion

This study investigates the impact of the ETS on a firm's TFP using the time-varying DID method. Our empirical results found that the ETS can significantly improve the TFP of firms, and these findings are consistent after numerous robustness checks.

Moreover, we further tested two channels through which the TFP is impacted: the corporate green innovation channel and the resource allocation efficiency channel. Our findings showed that both channels exist. On one hand, the ETS stimulates the firm's green innovation, and the green innovation reduces the firm's cost, which further improves the productivity of firms; on the other hand, the ETS improves resource allocation efficiency, production factors flow to sectors with high efficiency and clean technology, and then, the TFP of firms improved.

In addition, we analyzed the heterogeneity. First, in terms of corporate ownership, the impact of the ETS is significantly positive for private firms, whereas this impact is insignificant for SOEs. Moreover, from the perspective of regional differences, the impact of the ETS is more pronounced in provinces with more development of institutions, lower environmental quality, and higher enforcement of environmental regulation.

Data availability statement

Publicly available datasets were analyzed in this study. These data can be found at: CSMAR.

Author contributions

BW contributed to the conception and design of the study, MY organized the database and performed the statistical analysis, and XZ wrote the first draft of the manuscript.

Funding

This research is financially supported by the National Social Science Foundation of China (Grant No. 21BJY123) and The Humanities and Social Sciences Research Project of Chongqing Municipal Education Commission (Grant No. 21SKGH188).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 16 November 2022
DOI 10.3389/fenvs.2022.1025337

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OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Environmental Economics and Management,
a section of the journal Frontiers in Environmental Science

RECEIVED 22 August 2022
ACCEPTED 18 October 2022
PUBLISHED 16 November 2022

CITATION
Al-Saidi M (2022), Disentangling the SDGs agenda in the GCC region: Priority targets and core areas for environmental action.
Front. Environ. Sci. 10:1025337.
doi: 10.3389/fenvs.2022.1025337

Disentangling the SDGs agenda in the GCC region: Priority targets and core areas for environmental action

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The agenda of the Sustainable Development Goals (SDGs) is a key international outcome for guiding development efforts of nation states. However, SDG targets cover vast areas of action, and they are difficult to break down and monitor for countries with different developmental situations and needs. Often, global rankings of countries' compliance with the SDG agenda are plagued with false signals and methodological limitations. This paper presents a much-needed prioritization of the SDG targets for the Gulf Cooperation Council (GCC) region. It maps SDG targets and outlines priorities and key areas for environmental action. Sustainability in resource use, consumption and production constitutes a primary area for investments. Education and awareness represent cross-cutting priorities and low-hanging fruit for action. Tackling climate change and emerging supply risks and the management of ecosystems represent an action area in which GCC governments can intensify their interventions. As a supporting policy, regional environmental cooperation is important for enhanced commitments and tackling transboundary aspects of the SDG agenda. The analysis of the SDG agenda in the GCC regions reiterates the importance of countries engaging with global sustainability framings in order work out their own interpretations in congruence with national development realities. Such an SDG regional mapping exercise also assists national-level planners or regional bodies working on development issues in shaping the Gulf region's engagement with the global sustainability agenda and tracking progress on key SDG priorities.

KEYWORDS

sustainable development goals (SDGs), Gulf Cooperation Council (GCC), global sustainability agenda, sustainable consumption and production, ecological footprints, education for sustainable development

Introduction

The Sustainable Development Goals (SDGs) represent a key pillar of the global sustainability agenda, which also includes other global accords such as the 2015 Paris Agreement. Such globally endorsed agreements have set targets (for the year 2030 in the case of the SDGs and the Paris agreement) that serve as orientation frameworks for national policymaking. Success in achieving the SDG agenda is measured in terms of achieving the 169 SDG targets, which are comprehensive but with many trade-offs and synergies among them all (Kroll et al., 2019; Fonseca et al., 2020). In contrast to the Millennium Development Goals (MDGs, 2002–2015), the SDGs are not oriented towards underdeveloped countries. Their global validity stems from incorporating ambitious goals for countries at different levels of economic development. The SDG agenda also represents an umbrella for policies regarding low-carbon and green developments. However, not all SDG targets are relevant for all countries, and besides, the large number of targets can make it difficult to monitor and institutionalize progress towards the implementation of the SDGs. The upshot of this is that the periodic reports on progress towards the SDGs are often done in an *ad hoc* manner. Governments, national organizations, and companies tend to "cherry-pick" SDGs based on little analysis or insufficient explanations regarding their prioritization, leading to superficial implementation or merely symbolic commitment ("SDG-washing") (Forestier and Kim, 2020; Heras-Saizarbitoria et al., 2022).

Another problematic aspect of the implementation of the SDGs is that these goals largely lack consistent and evidence-based frameworks (Allen et al., 2018). Furthermore, the academic literature on the SDGs often lacks perspectives on integrated monitoring and evaluation (Bennich et al., 2020). As a result, there have been several calls for the development of more emphasis and prioritization in applying the SDGs at a regional or local scale. For example, Allen et al. (2017) suggested for the Arab world a prioritization of SDGs based on norms such as human dignity and well-being, natural resource protection, and peace. Similarly, Bissat and Rihan (2019) stress the importance of contextualizing the SDG agenda, and suggest peacebuilding and the reduction of inequalities as key issues for the Arab region. Other global prioritization endeavors suggest that a group of interlinked SDGs is more important than the other ones individually; e.g., SDGs 1, 2 and 6, since they are important for basic supplies and economic survival (Yang et al., 2020). So far, there has been no contextualization of the SDG priorities with regard to the Gulf Cooperation Council (GCC) countries of Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates (UAE).

It will remain challenging to break down the SDGs into more context-specific priorities. However, there is a pressing need for such a prioritization at the level of national states or of regions that share similar economic or hydro-climatic characteristics. Such a prioritization would help national governments better appreciate the SDG agenda and engage in implementation and reporting. This paper responds to this need by analyzing the prioritization and relevance of the SDG targets with regard to environmental action needs in the GCC region. Using mapping of targets and data from SDG monitoring instruments, the paper presents the priority targets for the GCC region. It later outlines the core areas of environmental action relevant to achieving the SDGs, and discusses the progress of GCC countries in these areas. In this sense, the paper provides valuable insights for policymakers in terms of priority issues for public investments and pathways for integrating the SDG agenda into local strategies.

Case study and justification

Relevance of the SDG agenda for the GCC region

The GCC region is composed of largely arid countries that are economically well developed. GCC countries share the same grand environmental challenges in terms of water scarcity, large ecological footprints, destruction of marine ecosystems, and the negative impacts of climate change (Saif et al., 2014; Al-Maamary et al., 2017; Burt et al., 2017; Al-Saidi and Saliba, 2019). For a long time, insufficient attention was paid to these challenges by policymakers who were (and probably still are) more oriented towards economic goals such as gradually diversifying government revenues while maintaining the high income levels of citizens and the generous benefits awarded to them by the state (Zaidan et al., 2019). Often in the past, environmental impacts of physical scarcity and environmental damage have been addressed in an *ad hoc* manner through water desalination, exchange of oil for food, and some environmental remediation of (marine) ecosystems (Sale et al., 2011; Woertz, 2013; Al-Saidi, 2019). After decades of economic growth powered by plentiful fossil-fuel revenues distributed to rather small populations, GCC states have recently become more engaged with the global sustainability agenda. While GCC states—led by Saudi Arabia—have for a long time tended to reject global environmental efforts such as climate agreements, they are now less skeptical regarding the global environmental governance system. Al-Saidi et al. (2019) have detailed how GCC countries have recently become interested in the global sustainability agenda through international agreements including the SDG agenda, the Paris Agreement, and several environmental regimes.

GCC countries are now engaged within frameworks that understand development from a comprehensive perspective; for example, they adopted the SDG agenda along with all its reporting and monitoring instruments. They have also sought to align this agenda with their national visions and mainstream parts of it in their regional (e.g., using GCC-wide instruments) or international (e.g., through engagement with UN-based actors or organizations such as the Global Green Growth Institute) state environmental relations (Al-Saidi, 2021). Furthermore, more comprehensive environmental approaches based on ideas such as resilience, ecosystem management, integrated management or inter-sectoral coordination are increasingly important for GCC states (Burt et al., 2017; Abulibdeh et al., 2019; Al-Saidi and Saliba, 2019).

The reasons for the increased sustainability engagement of GCC states are threefold. Firstly and most importantly, there are urgent economic consequences arising from increasing local demands due to population and economic growth. These growths have meant that the distributive nature of GCC states (low levels of taxation, attractive public jobs, subsidies for basic services such as water and energy, and individual subsidies for GCC nationals) are difficult to maintain in the long run, especially with fluctuating global energy prices (and hence fluctuating state revenues). For example, increasing local demands have necessitated reforms such as energy subsidy reductions and energy diversification (through renewables), as otherwise, GCC states might soon have to use all their fossil fuels destined for export to satisfy local consumption (Gately et al., 2012; Al-Saidi, 2022a). In fact, economic diversification through decreasing the reliance on fossil fuel revenues represents a paramount goal for the development strategies of GCC states.

Efforts to diversify GCC economies date back to the early 1970s, with little success in significantly lowering the dependence on fossil fuels (Albassam, 2015). Structural challenges to such diversification include the strong role of states and the lack of interregional trade or specialization among GCC states (Hvidt, 2013). GCC states have tried several tools for economic diversification, including sovereign wealth funds (El-Kharouf et al., 2010) and the introduction of environmental innovations (Al-Saidi and Elagib, 2018). Engagement with the sustainability agenda through, for example, the deployment of sustainable energy can help break up the high proportion of GCC economies tied up in the oil and gas sectors (Flamos et al., 2013). The challenges facing economic diversification in the Gulf region are also similar to those facing many developing countries, particularly fossil fuel-exporting economies (Mishrif, 2018). For example in Azerbaijan, state revenues from fossil fuel resources are economically significant, but they can be invested in diversification or economic modernization (Sadik-Zada, 2020; Sadik-Zada et al., 2021). Without a sustainable strategy for managing such revenues (e.g., through investments in sustainability efforts), oil-exporting countries risk economic slowdown (including the "Dutch disease" phenomenon of deteriorating economic performance despite fossil fuel exports) (Niftiyev, 2020; Niftiyev, 2021).

Secondly, international pressure on and expectations of GCC countries to engage with sustainability have increased in recent decades since these countries are often criticized for exhibiting large *per capita* consumption footprints and blocking some parts of the international climate agenda (Depledge, 2008; Krane, 2018). Thirdly and finally, the technological and economic feasibility of many environmental technologies has provided "win-win" opportunities for GCC countries to satisfy environmental requirements and save costs or attract investments. For example, GCC states are now interested in an "ecological modernization" through "eco-innovations," particularly in the built environment, in order to maintain their modern images and attract high-value residents and investors (Al-Saidi and Elagib, 2018). Furthermore, engaging in the energy transition agenda is worthwhile since saved revenues from energy subsidy reductions can be redirected towards more productive uses (e.g., development of renewables or direct welfare transfers) (Abdel Gelil et al., 2017; Al-Saidi, 2022a). Moreover, renewable energies (particularly solar energy) have proven to be very economical in the Gulf region, with new photovoltaic plants producing energy at world-record prices (e.g., 0.01 USD per Kwh) (Bellini, 2021).

SDGs monitoring and (false) signals

Progress reporting on the SDG agenda is carried out using the periodic Voluntary National Reviews (VNRs), which all countries submit to the High-level Political Forum (HLPF) of the United Nations (UN). However, these reviews are often unspecific, and they include descriptive listings of achievements based on the progress of achieving local policies, or overarching national visions (Al-Saidi, 2021). Global monitoring instruments such as the SDG index can give incoherent or false signals. Table 1 provides a comparison of the SDG rankings of GCC countries in 2017 and 2020, and shows significant discrepancies, particularly with regard to SDGs 11, 13, 14, and 15. This is due to the reliance on a small set of indicators, sudden changes in indicator values, or the specific sets of indicators used for the respective SDGs. For example, on SDG 13, Qatar dropped from 59 in 2017 to 15 in 2020. This was due to a change in value of the indicator "imported CO_2 emissions, technology-adjusted (tCO_2/capita)" from a good value of -6.5 in 2017 to a bad value to of 1.7 in 2017. Furthermore, among the three indicators used for this SDG, the "Climate Change Vulnerability Index" used in 2017 (with Qatar scoring well) was replaced in 2020 with the indicator "CO_2 emissions embodied in fossil fuel exports (kg/capita)" (with Qatar performing badly). These inconsistencies are also present in other SDGs not shown in Table 1. For example, the UAE's score on SDG 17 (partnership for the goals) dropped from 100 in 2017 to 51 in 2020, due to a value change of just one indicator. The UAE scored 0 on the indicator "tax haven score (best 0–5 worst)" in 2017, and in 2020, the score changed to 98.3 on the new but very similar indicator of "Corporate Tax Haven score (best 0–100 worst)".

TABLE 1 Scoring of GCC countries on environmentally relevant goals in the SDG index (data source: Bertelsmann Stiftung and Sustainable Development Solutions Network, 2017; Bertelsmann Stiftung and Sustainable Development Solutions Network, 2020).

GCC Country	Index Score[a]		Index Rank[b]		SDG 6[a]		SDG 7[a]		SDG 11[a]		SDG 12[a]		SDG 13[a]		SDG 14[a]		SDG 15	
	y20	y17	y20	y17	y20	y17	y20	y17	y20	y17	y20	y17	y20	y17	y20	y17	y20	y17
Bahrain	69	65	82	92	71	50	94	89	52	70	68	74	63	50	65	31	61	40
Kuwait	63	62	112	102	49	49	93	86	54	26	37	24	34	59	51	36	55	40
Oman	70	64	76	94	51	50	87	79	78	67	72	61	64	74	70	55	57	37
Qatar	65	63	103	98	57	49	89	78	36	47	70	57	15	59	61	39	58	40
SA	66	63	97	101	48	58	89	83	42	0	66	59	59	73	60	46	49	35
UAE	70	66	71	77	56	50	91	83	78	31	52	45	29	48	67	48	58	29

[a]Score range from 0 to 100.
[b]Rank in the SDG, index among 166 countries.
Abbreviations: y20, value for the year 2020; y17, value for 2017; SA, saudi arabia; UAE, the United Arab Emirates; SDG 6, Clean Water and Sanitation; SDG 7, Clean and Affordable Energy; SDG 11, Sustainable Cities and Communities; SDG 12, Sustainable Consumption and Production; SDG 13, Climate Change; SDG 14, Life below Water; SDG 15, Life on Land.

Mapping methodology and outcomes: Steps for outlining SDG regional relevance

The highlighted problems with global rankings and monitoring instruments illustrate the need for more consistent assessments based on local or regional realities. There is evidence that national governments do not care about all SDGs in the same manner, but rather prioritize them in accordance with their existing national development policies. Studies examining national policies have developed several specific SDG priorities, such as high-income countries prioritizing SDGs related to economic development (e.g., SDGs 1 and 8) (Forestier and Kim, 2020). Similarly, small-island states tend to give more weight to economic and societal SDGs; e.g., SDGs 2, 3, 4, 8 and 9 (Eppinga et al., 2022). There are also several studies that suggest normative SDG prioritizations based on general development needs or the relevance of particular concepts for a certain region. For example, during the implementation of the SDG agenda, the Arab region might emphasize issues such as human dignity and its linkages to natural resources, governance, and peace (Allen et al., 2017). Hepp et al. (2019) see gender equality (SDG 6) as a cross-cutting and central priority across the whole SDG agenda. In the wake of COVID-19, several studies have argued for concepts such as the circular economy, green management, and green recovery as some of the central aspects of the SDG agenda (Sharma et al., 2021; Shulla et al., 2021; Ameli et al., 2022).

The methods and criteria used for selecting relevant SDGs or appropriate SDG policies in the pertinent academic literature largely depend on the goal of the mapping exercise. Arguably, a large number of publications using SDG mapping have sought to identify trade-offs, interdependencies or synergies in a general conceptual manner or applied to a specific (national) case (e.g., Fuso Nerini et al., 2018; Breuer et al., 2019; Kroll et al., 2019). The SDGs have also been examined with regard to certain types of enabling policies; e.g., required economic policies in Africa (Basheer et al., 2022). There are only a handful of publications seeking to outline the relevance of the agenda and regional SDG priorities. Forestier and Kim (2020) offered a prioritization exercise for 19 countries at varying economic levels (and from different regions) using both VNR declarations and quantitative indicators related to aid flows. There are SDG mappings on more coherent regions such as the SDG ranking in small-island states using students' surveys by Eppinga et al. (2022).

For the Arab region, Allen et al. (2017) relied on indicator-based assessment of SDG indicators to conclude some missing gaps to be addressed or prioritized in future action. Similarly, Allen et al. (2018) reviewed SDG progress in the Arab region using VNRs and the academic literature to identify policy-level gaps (e.g., the need for more integrated and comprehensive action). In contrast, this paper proposes an SDG mapping of a region that is arguably socio-economically and politically quite coherent. It also uses a qualitative analysis of self-declared policies by GCC states and reviews the academic literature for contextualization. It relies on the study of national development policies since they are the main formal guidance for national development efforts. As previously mentioned, VNRs can include some bias as they are often designed to satisfy UN-level reporting requirements through listing achievement points and showcasing compliance. In addition, gauging stakeholders' perceptions of priorities (e.g., through interviews and surveys) poses methodological challenges with regard to its feasibility and representativeness in evaluating perceptions on an all-encompassing agenda with an unmanageable number of targets.

This paper proposes a mapping of the SDG targets in order to gauge the relevance of specific SDGs for the GCC region based on an analysis of national-level policies, with a particular focus on environmental outcomes. The mapping methodology will be

FIGURE 1
Mapping of relevant SDG targets for the GCC region.

explained in this section. The first step was to eliminate non-relevant targets, and hence the mapping results (Figure 1) show only slightly, moderately, or highly relevant targets. The targets not shown in this mapping are deemed to be of no relevance due to high achievement or high economic development levels. These are largely targets related to poverty, food security, access to basic services, control of infectious diseases, and safety, all of which are more oriented towards developing or least-developed countries. Secondly, the SDG targets with little or unclear relevance represent issues based on either one of the following criteria: They should have not been highlighted as relevant areas either in national policies such as national visions or corresponding by-laws and strategies. Alternatively, the relevance of some of these targets can be unclear due to the lack of data on compliance with these targets. The targets include issues such as official development assistance (ODA) for certain areas, specific forms of crime, or specific inequality indicators.

Thirdly, targets with moderate relevance are determined based on the baseline criteria of being mentioned in national policies as important issues as well as on three additional criteria: that 1) the performance of the GCC states on these issues is relatively fair, 2) the issues are not marked as (high) priorities in national policies, and/or 3) the issues are of limited national relevance. Examples of the first criterion include unemployment, wildlife protection, public transport and open spaces, hazardous waste, performance of public institutions, illegal fishing, or fishers' income. The second criterion covers targets such as agricultural support, substance use, or women's participation as a few examples that are mentioned in national policies but do not present pressing issues or are not consistently marked as (high) priorities. For the third criterion, as an example, the GCC region is not prone to natural disaster such as droughts or floods, although the issue of disaster risk is still important due to the potential for industrial accidents, heatwaves, or occasional storms, which are an issue in Oman, for example. In this case, SDGs related to disaster damage are only moderately relevant, while SDGs related to disaster management itself are highly relevant. Furthermore, the region does not feature a wide cover of mountains and forests, although these issues can be relevant in some areas in Saudi Arabia or Oman.

In the final step, targets designated as highly relevant are determined based on two baseline criteria of 1) uncompetitive scoring on these goals and 2) being mentioned as high priorities in national strategies. To arrive at these targets, national development policies (i.e., national visions and corresponding implementation strategies) were screened using qualitative research support systems (the software MAXQDA). In the event that any text on policies or targets was evaluated to be relevant to a certain SDG target, it was coded to correspond to that target. The screening of these strategies was applied for each SDG target, but the resulting grouping of targets was sequential. This means that targets not highlighted in strategies were added to an initial group and later checked across other criteria (earlier mentioned in Steps 1 and 2) to determine targets of no or little relevance. The remaining targets (i.e., those mentioned in national strategies as relevant issues or high priorities) were assigned to the group of moderately or highly relevant targets (Steps 3 and 4). The other criteria for moderately relevant targets (Step 3) resulted in a narrowing of the remaining targets. In the final step (4), only those targets that are explicitly mentioned as high priorities remained, and they were checked against the additional necessary criterion of uncompetitive scoring of GCC states. Most of these highly relevant targets are environmental ones, which will be detailed in the next section with regard to their relevance but also to the underachievement of GCC states of these targets.

In addition to these environmental targets, other highly relevant targets included tourism's contribution to GDP, the situation of the labor workforce, industrial development, traffic safety, and societal participation. In general, there is a large number of indicators that can be used to verify the scoring of GCC states on any one SDG target, although presenting such indicators on the large number of targets is beyond the scope of this paper. Arguably, the performance of GCC states in these areas lags behind that of benchmark countries. For example, on non-environmental targets deemed highly relevant, one can cite road traffic accidents as a major cause of death in the Gulf region (Dahim, 2018). The situation of the labor workforce in the immigration-dependent Gulf region is a much publicized debate that includes tackling mobility restrictions of labor (e.g., sponsorship requirements or migration costs), or occupational injuries—all subjects of recent reforms by GCC states (Aarthi and Sahu, 2021). Tourism and its contribution to GDP is a major theme for GCC diversification efforts, with GCC states still dependent on fossil fuel revenues and lacking foreign direct investments (with the exception of the tourism hotspot of Dubai) (Eissa and Elgammal, 2019; Scharfenort, 2020). In addition, industrial development is weak with the exception of extractive industries. Finally, societal participation is important as GCC states still face important challenges with regard to gender equality issues such as women's labor participation (Murray and Zhang-Zhang, 2018).

Results: Core areas for environmental action

The primacy of sustainable resource use, production, and consumption

A primary area for environmental action in the GCC region is encouragement of the sustainable use of the key resources of water and land, and reducing the large footprints of consumption and production. Table 2 presents some data showing the high pressure on freshwater resources and the comparatively large consumption and production footprints. Water overuse and scarcity, and hence the scarcity of arable land for agriculture, have been major concerns in the region, and as a result, issues such as sustainable agriculture, water use efficiency and integrated water management represent paramount priorities (Saif et al., 2014; Brown et al., 2018). Furthermore, in comparison to high-income countries, the levels of energy intensity, emissions footprints, and air pollution due to fuel burning and construction are relatively high (Table 2). This necessitates the prioritization of SDG targets related to sustainable production, footprints, and sustainable urban planning. Issues such as tackling pollution, lowering ecological footprints, and achieving renewables targets have thus been incorporated in the national visions of all the GCC states (Al-Saidi and Elagib, 2018).

Table 3 shows the relevant environmental SDG targets for the different environmental action areas. There are several targets associated with sustainable resource use, consumption, and production, which largely focus on reducing production and consumption footprints. Issues such as water management in general and solid waste management are classic priorities in the GCC region. GCC states have developed several national and regional policies to tackle water stress, expand water (re)use options, and establish integrated plans (Aleisa and Al-Zubari, 2017; Zubari et al., 2017). Solid waste management practices are increasingly encouraging activities based on the circular economy and recycling (Hahladakis and Aljabri, 2019; Alagha et al., 2022). Lowering the footprints of consumption and production is still an important action area in the GCC region, which exhibits 2.5 to 3 times higher domestic material consumption *per capita* in comparison to the global average (ESCWA, 2021). The large production and consumption footprints are associated with urban lifestyles, construction activities, and expansion of the built environment. Therefore, sustainable urbanism is a directly associated priority, and it can be enhanced through circular economic interventions including recycling, sustainable urban agriculture, and water reuse (Al-Saidi et al., 2021). In addition, the tourism sector is responsible for large amounts of resource waste (including food waste), and so should be targeted for environmental action by GCC governments (Pirani and Arafat, 2016).

TABLE 2 Selected indictors on resource availability and use footprints in the GCC region.

	BHR	KWT	OMN	QAT	SAU	ARE	MENA	HIC
Freshwater withdrawals (% of available freshwater resources)[a]	133	3,851	117	431	992	1,667	234	81
Energy intensity level of primary energy (MJ/$2011 PPP GDP) (2015)	2.7	1.5	1.8	1.8	1.6	1.4	1.5	1.3
CO_2 emissions from fuel combustion for electricity and heating per total electricity output (mtCO2/TWh) (2017)	1.1	1.3	1.9	1.9	1.6	1.6	1.6	1.2
Annual mean concentration of particulate matter of less than 2.5 microns in diameter (PM2.5) (μg/m3) (2017)	70.8	60.7	41.1	91.2	87.9	40.9	56.8	14.6
Domestic material consumption per capita, by type of raw material (tonnes) (2017)	28.5	29.6	31.7	49.9	25.0	22.5	NA[c]	NA[c]
Municipal solid waste (kg/capita/day)[b]	1.9	1.1	1.2	1.0	1.6	1.8	1.2	1.9
Production-based SO_2 emissions (kg/capita) (2012)	87.5	284.2	49.4	66.7	72.3	43.4	25.4	54.6
Energy-related CO_2 emissions (tCO_2/capita) (2017)	15.5	23.3	13.2	44.0	17.9	23.5	5.9	10.5

[a]Years of values: 2015 MENA, and HIC, 2018 for the remaining values.
[b]Years of values: 2014 for Oman, 2015 for KSA, 2012 for Qatar, 2010 for Kuwait, 2016 for the remaining values.
[c]Average value for the world: 11.7; and for Europe and Northern America: 15.2.
Abbreviations: BHR, bahrain; KWT, kuwait; OMN, oman; QAT, qatar; SAU, saudi arabia; ARE, united arab emirates; MENA, middle east and north africa; HIC, High-income countries.
Sources: UN, Stats (unstats.un.org/sdgs/indicators/database/) for the two indices of freshwater withdrawal and domestic material footprint; and Bertelsmann Stiftung and Sustainable Development Solutions Network (2020) for the remaining indices.

TABLE 3 Linking SDG targets to core areas for environmental action in the GCC region.

Core environmental action areas	Directly relevant targets	Closely associated targets	Broad and cross-cutting targets
Sustainable resource use, production, and consumption	Material footprint (8.4.1., 12.2.1), domestic consumption (8.4.1, 12.2.2), sustainable production (2.4.1), solid waste management (11.6.1), sustainable consumption plans (12.1.1), global food loss (12.3.1), recycling rates (12.5.1), water use efficiency (6.4.1), freshwater stress (6.4.2), integrated water management (6.5.1)	Sustainable urbanization (11.3.1), CO_2 emissions intensity (9.4.1), urban air pollution (11.6.2), sustainable tourism jobs (8.9.2), sustainable tourism (12.b.1)	Policy for sustainable development (17.14.1), sustainable public procurement (12.7.1), corporate sustainability reports (12.6.1)
Marine protection and ecosystem management	Degraded land (15.3.1), red list index (15.5.1), invasive alien species (15.8.1), biodiversity planning 15.9.1), water ecosystems (6.6.1), marine (plastic) pollution (14.1.1), marine ecosystem management (14.2.1), ocean acidification (14.3.1), fish stock levels (14.4.1), marine protected areas (14.5.1)	Sustainable urbanization (11.3.1), sustainable tourism jobs (8.9.2), sustainable tourism (12.b.1)	
Climate change, supply security and emergent risks	CO_2 emissions intensity (9.4.1), air pollution deaths (3.9.1), disaster risk reduction (1.5.3, 11.b.2), local disaster risk (1.5.4, 11.b.1), integrated climate policies (13.2.1)	Renewable energies (7.2.1), clean energy investment (7.a.1), urban air pollution (11.6.2)	
Education for sustainable development	Education for sustainable development (4.7.1, 12.7.1), climate change education (13.3.1), climate change capacity-building (13.3.2), research for marine technology (14.a.1)	R&D spending (9.5.1), R&D researchers (9.5.2)	

Marine protection and ecosystem management as recurrent priorities

Another core area for environmental action is represented by SDG targets to preserve ecosystems, particularly marine and water ecosystems, in the GCC region. Marine ecosystems have important cultural and economic values in the region, but they have suffered from coastal construction, land reclamation, plastic pollution, and climate change impacts (Sale et al., 2011). For this reason, expanding and enforcing

TABLE 4 Ecosystem management and climate change in formal policymaking through national visions of GCC states.

Country*	Area	Specific perceptions in national visions	Specific measures in implementation policies of national visions	Environmental ministries
Bahrain	Ecosystem management	No direct mention in 2030 National Vision; a part of the goal of "Conserving our natural spaces for future generations to enjoy (page 22)"	Two goals in National Action Plan 2019–2022: i) activate monitoring of protection of marine areas. ii) Continue to preserve and ensure sustainability of marine resources	Municipalities and agriculture; oil and environment
	Climate change	NA	NA	
Kuwait	Ecosystem management	No explicit mention in New Kuwait 2035	Not a part of projects listed in the Development Plan related to New Kuwait 2035	Ministry of Water, Electricity and Renewable Energies
	Climate change	NA	NA	
Oman	Ecosystem management	A part of the priority "environment and natural resources" in Oman Vision 2040; mentioned within the objective of "environmental ecosystems that are of high quality and free from pollution" as well as implicitly in other objectives (e.g., "balanced environment", "sustainable use of natural resources", "optimal exploitation of the strategic location and biodiversity") within the mentioned priority	Implicit measures mentioned in the 10 h 5-year plan related to environmental awareness and improvements of environmental legislation	Ministry of Agricultural, Fisheries Wealth and Water Resources
	Climate change	Mentioned under the objective "Urban and rural areas and cultural and natural heritage regions that are highly resilient and capable of coping with climate change effects" in the priority "Development of governorates and sustainable cities" of Oman Vision 2040	Repeatedly mentioned in the 10th 5-year plan as a broader challenge to be addressed through environmental objectives related to resource security, circular economy, green economy, awareness, etc.; explicitly mentioned in the measure to "improve protected areas that respond to climate and environmental change and activate early warning systems for natural disasters"	
Qatar	Ecosystem management	Mentioned as a major outcome of "sustainable development" pillar of Qatar National Vision 2030, namely "Preserving and protecting the environment, including air, land, water and biological diversity" through several measures	Measures included in Qatar National Vision 2030 included environmental awareness, environmental institutions, and environmental legislations; several measures mentioned in Qatar's National Development Strategy (2011–2016) including a National Water Act, national biodiversity database, effective management of protected areas, and environmental projects; measures mentioned in Qatar's National Development Strategy (2018–2022) including the development and implementation of a comprehensive coastal marine quality control plan and an integrated plan for protected areas and other ecosystems, the creation biodiversity database, the promotion of environmental awareness	Ministry of Environment and Climate Change
	Climate change	Mentioned as main outcomes within the "sustainable development pillar of Qatar National Vision 2030, namely to" proactive and significant regional role in assessing the impact of climate change and mitigating its negative impacts, especially on countries of the Gulf" and "to Support for international efforts to mitigate the effects of climate change"	Measures mentioned in Qatar's National Development Strategy (2011–2016) including eliminating excess ozone levels through air quality management, halving has flaring; measures mentioned in Qatar's National Development Strategy (2018–2022) including creating an integrated national air quality management plan, and establishing green belt around Doha	
Saudi Arabia	Ecosystem management	Implicitly mentioned in Saudi Vision 2030 under the goal of "achieving environmental sustainability" through aspiration to "preserve environment and natural resources", "reducing all types of pollution" and "rehabilitating beautiful beaches, natural reserves and island"	No explicit programs under the Vision Realization Programs of Saudi Vision 2030; reported in the vision's progress under the Saudi Green Initiative which includes one (of four) targets on "protecting land and sea" through initiatives including establishing and sustainability managing nature reserves, expanding protected areas with integrated management	Minister Of Environment, Water and Agriculture

(Continued on following page)

TABLE 4 (*Continued*) Ecosystem management and climate change in formal policymaking through national visions of GCC states.

Country*	Area	Specific perceptions in national visions	Specific measures in implementation policies of national visions	Environmental ministries
	Climate change	NA	No explicit programs under the Vision Realization Programs of Saudi Vision 2030; reported in the vision's progress under the Saudi Green Initiative under the target of "reducing emissions") through initiatives to capture and use carbon, and energy reforms (e.g., increasing efficiency and introducing renewables)	
United Arab Emirates	Ecosystem management	Mentioned within Target 4.4, "Well-preserved natural environment" of the UAE National Vision 2021 including issues such as environmental protection, environmental awareness, reducing human-induced threats, regulations to defend ecosystems from urban development; implicitly mentioned in Abu Dhabi Economic Vision 2030, within Objective 24 on "environmental sustainability" including environmental compliance	NA	Ministry of Climate Change and Environment
	Climate change	Mentioned within target 4.4. "Well-preserved natural environment" of the UAE National Vision 2021 including issues such as emissions reductions	NA (note)	

NA: Not available. If it was not possible to find any direct or relevant indirect references to the issues of ecosystems management or climate change in the national visions or associated implementation policies/plans.

*The launch years for the national visions indicated in () are as follows: Bahrain National Vision 2030 (2008), Kuwait National Development Plan 2035/New Kuwait (2017), Oman National Vision 2040 (2020), Qatar National Vision 2030 (2008), Saudi Vision 2030 (2016), UAE National Vision/Agenda 2021 (2010).

the protection of ecosystems and adopting comprehensive strategies of ecosystem management are recurrent priorities in the region (Burt et al., 2017). Environmental protection through the designation of protected areas has been an important instrument in the sustainability policies of GCC states (Al-Saidi, 2021). The management of marine ecosystems has also been a recurrent cooperation priority for the wider Gulf region, including all Gulf countries signing the Kuwait Regional Convention for Co-operation on the Protection of the Marine Environment from Pollution of 1983 (Al-Saidi, 2022b). However, these ecosystems have become increasingly affected by urban expansion (including impacts of the disposal of desalination brine), climate change (including fish deaths and coral bleaching), or (plastic) pollution (including coastal tourism activities) (Sale et al., 2011; Ben-Hasan and Christensen, 2019; Paparella et al., 2019; Hosseini et al., 2021).

Table 4 shows how the issues of ecosystem management and climate change are anchored in national visions and their associated implementation policies. The protection of terrestrial and marine ecosystems is a main theme within national policies and is often connected to broader issues such as heritage preservation, environmental awareness, and environmental legislation. With regard to marine ecosystems, GCC states seem to incorporate less specific measures than they do for terrestrial ecosystems. This might be related to the transboundary issues associated with these systems as well as the complex set of challenges facing them. The main proposed instruments to expand the protection of these systems are enhancement of monitoring activities and environmental legislation. Scholars have stressed the need to adopt a comprehensive set of measures towards integrated ecosystem management in the Gulf (Burt et al., 2017). Only Qatar and Saudi Arabia have explicitly incorporated in their national visions the idea of ecosystems management as an all-encompassing approach. The concept of integrated management based on linking different uses and issues of a particular environmental ecosystem is, however, incorporated into several environmental SDG targets (e.g., 6.5.1, 6.6.1 and 14.2.1). Overall, Qatar seems to have the most detailed measures in this area of ecosystem protection and management. However, considering the totality of ambitious measures in Qatar's first and second National Development Plans, progress on these targets is ongoing.

Climate change, supply security, and emergent risks

Climate change is expected to be a major threat in the GCC region, with climate extremes such as heatwaves affecting supply provision, health, and marine ecosystems (Al-Maamary et al., 2017). However, climate change has not featured highly in national policymaking in the GCC, despite GCC states suffering significantly from extremes such as heatwaves, with multiple important impacts, particularly on marine ecosystems (Al-Saidi et al., 2018; Hereher, 2020). GCC states have historically been skeptical to climate change action (Depledge, 2008), rather treating climate action more practically, in terms of expanding renewable energies and modernizing the built infrastructure (Al-Saidi and Elagib, 2018). These modernization efforts include building certifications, investments in public transport, and the expansion of the use of electric vehicles (particularly in the UAE). Investments in renewable energies have also increased significantly in the last decade, with all GCC countries incorporating solar energy in ambitious renewable targets; e.g., 50% of power production by 2030 in Saudi Arabia (by far the largest economy) (Amran et al., 2020; Barhoumi et al., 2020; AlShammari, 2021).

Table 4 shows the incorporation of the climate change issue in the national agendas of GCC countries. Overall, more recent policies seem to incorporate more environmental protection issues than older ones, with the notable exception of Qatar incorporating climate change as a key theme in its 2008 national vision. Qatar's interest in climate change might have increased ahead of hosting the 2012 Conference of Parties (COP 18) of the UN Framework Convention on Climate Change (UNFCCC). After the decline in oil prices in 2013/14, many GCC countries became cautious regarding bold action on climate change (Al-Saidi et al., 2018). Recently, some GCC states (particularly Qatar, Saudi Arabia, and the UAE) seem more engaged with the climate issue, as evident in the establishment of climate change ministries (Qatar and the UAE) or bold climate-related programs (e.g., the Saudi Green Initiative). This can be partly explained through increased interest of these countries in attracting major events or prestigious projects (e.g., Expo 2020 in Dubai, the 2022 World Cup in Qatar, the 2023 COP-28 in the UAE, or major planned cities such as NEOM in Saudi Arabia).

Alongside climate change-related targets, SDG targets related to disaster risk assessment, management and reduction are important due to the mounting risks facing the largely costal supply infrastructure; e.g., desalination and electricity plants, aquaculture, or coastal industry. These risks can stem from industrial accidents, human failure, attacks by non-state actors, or failures due to increased integration of water and energy production through large-scale plants supplying major cities in the GCC region (Al-Saidi and Saliba, 2019). Therefore, SDG targets related to disasters, risks and risk reduction are highly relevant for GCC states. Many of these states have recently shown a strong interest in enhancing their preparedness through strengthening disaster-risk and emergency institutions. However, most of them still lack a broader approach in terms of resilience-based policies, or the adoption of explicit integrated climate policies (SDG 13.2.1).

The missing link of education for sustainable development

Education to increase awareness of sustainable development and climate change has been mentioned in several SDG targets, and it is a key priority for the GCC region as a means of addressing the large ecological footprints, encouraging sustainable consumption, and increasing societal resilience to threats such as climate change. In fact, education for sustainable development (ESD) has been promoted worldwide as a way forward for education establishments (particularly higher education institutions) in order to capture the full benefits of an SDG-driven sustainability transition (Kioupi and Voulvoulis, 2019). The need for enhancing education on sustainability is also mentioned as a priority in national GCC strategies, and it is a common theme in regional policies (Al-Saidi, 2021). There is, however, little knowledge on the current efforts of GCC states to achieve this target, while the GCC's NVRs on the SDGs provide little information in this regard. In GCC states such as Qatar, ESD is still in its early stages and lags behind benchmark countries in the global South, such as Singapore (Fekih Zguir et al., 2021).

In the GCC region, it is rather rare to find specialized higher educational programs on major environmental issues such as natural resources management, climate change, sustainable agriculture, and clean energy. Paradigms such as the knowledge-based economy (KBE) have been used to guide future development. However, the practical focus in the interpretation of this paradigm in the GCC region is to encourage economic sectors with a high added value (hence economic diversification and entrepreneurship) through investing in education in the Science, Technology, Engineering and Mathematics (STEM) fields (S. Aldulaimi et al., 2020; Kayan-Fadlelmula et al., 2022). With environmental awareness arguably low and consumption footprints relatively high, EDS can play an important role for a sustainable future in the region beyond any economization considerations. The SDG agenda also stipulates that ESD should be accompanied by investments in R&D in order to encourage the development of clean technologies. GCC states are increasingly interested in research and innovation investments within their KBE strategies (Wiseman and Anderson, 2012). Considering the political economics of the GCC region, it remains open as to whether this approach based on KBE and mainstreaming elements of the ESD agenda can genuinely produce more sustainable lifestyles and an overall lower metabolism. Critics argue that mainstreaming the SDG agenda does not challenge the *status quo* and that sustainability education should rather encourage degrowth and environmental ethics (Kopnina, 2020). The SDG agenda also disseminates universal (neoliberal) premises that are often not embraced in Arab or GCC communities through corresponding cultural values that reflect a meaningful sustainability (Al-Zo'by, 2019).

Discussion: Aligning the SDG agenda to national and regional strategies

Mapping the SDGs for the GCC region provides opportunities for policymakers to align their national strategies to the global sustainability agenda and identify future areas for development-related investments. The analysis of SDG priorities for the GCC region allows for some observations to be summarized in this section.

Firstly, GCC states can improve their SDG rankings substantially through action in the highlighted environmental areas. While they seem to underachieve SDG targets in these areas, the mapping exercise has shown that the environmental targets represent the bulk of priority SDG targets for the region. In view of this, one way to implement these targets is to better align the SDG agenda to national strategies. So far, national visions, and particularly more recent ones such as the 2016 Saudi Vision 2030, refer explicitly to environmental action, but they rarely mention global agreements such as the SDGs. By prioritizing and disentangling the SDG targets for the GCC region, states can better link local action to the global targets. For this to happen, GCC countries need to realize the benefits of global environmental agreements such as the SDG agenda. This agenda has been heralded as "transformative" in terms of reflecting and addressing contemporary challenges, in contrast to previous global agendas (e.g., the Millennium Development Goals or MDGs), which focused on the priorities of the developing world (Fukuda-Parr, 2016; Stevens and Kanie, 2016). Embracing such an agenda and linking sectoral policies as well as national ones to global goals can improve the mobilization of funds, cross-sectoral cooperation, and policy impacts (Weitz et al., 2018; Zhan and Santos-Paulino, 2021).

Secondly, for the facilitation of SDG-related environmental actions, GCC states can start with low-hanging fruit such as education, local participation, and awareness of sustainable development, climate change and sustainable consumption. These issues are both separate SDG targets and preconditions for achieving other environmental targets. While this paper has focused on environmental issues, SDG mapping studies from the Arab region (with no study so far from the Gulf region) have emphasized similar soft issues such as participation, empowerment (e.g., through education) and integrated policymaking (Allen et al., 2018; Bissat and Rihan, 2019; ESCWA, 2021). At the same time, more demanding efforts in restructuring GCC economies towards clean production and low-carbon development should be sought in parallel, although the results of these efforts require serious commitments and will take some time to materialize. GCC countries can benefit from a speedier and easier implementation of the SDG agenda since they suffer less from the financial and institutional shortcomings common in order Arab countries. The persistence of diseases, poverty, and lack of expenditure can hinder the attainment of SDGs in other Arab countries, leaving the most vulnerable people behind (El-Zein et al., 2016). In prioritizing action on the SDG agenda, other Arab countries might have to start with the most basic and urgent reforms such as fiscal reform, fighting corruption, and peacebuilding (Bissat and Rihan, 2019). In contrast, GCC countries enjoy well-functioning institutions and economically prosperous societies, but they still lag behind comparable countries on environmental action.

Finally, the notion of environmental action constituting the bulk of SDG priorities in the Gulf region has implications beyond national policies. Many of the highlighted environmental priorities are transboundary by nature; e.g., climate change and related disasters, or the protection of the ecosystems of the Gulf water body. There has been little cooperation on these natural transboundary issues, although there has been success on water pollution in the Gulf (Al-Saidi, 2022b). Transboundary cooperation can increase the resilience of GCC states in facing global change impacts affecting their basic supply securities (Al-Saidi and Saliba, 2019). GCC-wide cooperation has left long legacies and has also covered important areas such as integrated grids, sustainable agriculture, hazardous waste, and (environmental) education (Al-Saidi, 2021). However, this cooperation does not capture the full potential of environmental cooperation on issues such as climate change, energy transition policies, or infrastructure. There are currently plans to enforce this cooperation through, for example, regional climate change research, completing integrated rail networks, and building environmental alliances (e.g., the Green Middle East Summit first held in 2022 in Saudi Arabia). Scholars also call for a wider Gulf region cooperation approach that includes researchers and civil society in order to harness the full benefits of science diplomacy in tackling common environmental challenges (Fawzi et al., 2022).

Conclusion

The SDG agenda represents an important and commonly accepted pillar of the global sustainability agenda. SDG goals and targets are supposed to guide the development agenda of nation states until the year 2030. The SDG agenda is ambitious and comprehensive as it includes a wide range of targets. The monitoring and assessment of progress towards achieving the SDGs have been difficult tasks due to the heterogeneity among the development needs and levels of countries, and the inadequacy of global comparisons through rankings and indices. Therefore, a prioritization of this agenda at the level of states or relatively homogenous regions such as the GCC region is valuable. The mapping exercise of the SDG targets in the case of GCC states has shown the importance of environmental targets for the region. GCC states seem to be joining the global consensus on major developmental priorities, particularly on SDGs related to clean energy, efficiency in resource use, and low-carbon development. The SDG agenda is an attractive paradigm for GCC states since it is also linked to other global endeavors endorsed by GCC states such as energy transition policies and climate change agreements (e.g., the 2015 Paris agreement).

The core areas for environmental action have been delineated. They include sustainable resource use, sustainable production and consumption, ecosystem protection and management, risk management including climate change, and sustainable development education. By addressing targets in these areas and aligning national strategies to the SDG agenda, GCC states can improve environmental outcomes and their global standings in regard to sustainability. They can immediately target low-hanging fruit such as education and awareness while facilitating demanding actions such as clean or circular production, energy transition, and low-carbon development. Regional cooperation can also accelerate the adoption of a transformative agenda in the GCC based on the SDG accord. Many of the demanding SDG targets demand action beyond national boundaries and beyond the capacity of states to influence outcomes. Global and regional change pressures related to increased resource use, damage to transboundary natural resources, and climate-related extremes require region-wide responses. Increasing research-based cooperation or the inclusion of civil society actors can help improve environmental education and awareness, which represent key missing links in the transition to sustainability in the Gulf region.

The study of the prioritization of SDGs in this paper has relied on explicit referencing of national policies or documented evidence of national relevance provided in the academic literature. Future research can focus on local perceptions on the relevance and merits of the SDG agenda, which, arguably, is little manifested in community-level development practices. The core sustainability values are challenged by the contemporary lifestyles in the Gulf, which often involve consumerism and hence large ecological footprints. Factors influencing a bottom-up transition to sustainability in the Gulf region are largely understudied. Understanding the merits of participatory, multi-stakeholder sustainability approaches in implementing the SDG agenda requires the embracing of single SDG targets and contextualizing the role of non-state actors such as the private sector or civil society. Such future research endeavors can provide a more nuanced view on the reception and acceptance of the SDG agenda in the Gulf.

This paper has shown that the global premise of the SDG agenda (i.e., comprehensive development issues reflecting key challenges involving all countries) can be confirmed in the Gulf region only with regard to the environmental agenda. While the GCC region exhibits a high compliance with many of the economic goals related to basic supply, it still has a long journey ahead in fulfilling core environmental targets. Indeed, environmental SDGs might be quite challenging for the majority (if not all) countries worldwide. This notion underscores the contemporary nature of the SDG agenda. In analyzing how national or regional priorities define the relevance of the SDG agenda, it becomes clear that this agenda has in fact different foci and mini-agendas constituting subsets of highly urgent and highly important targets that correspond to a similar subset of countries. In the example of the Gulf region, the relevant SDG (mini-)agenda is still broad and covers social (e.g., targets related to institutions, equality, and rights), economic (e.g., infrastructure and diversification), and environmental pillars, with the latter at the core of sustainable development priorities in the Gulf region.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

The author confirms being the sole contributor of this work and has approved it for publication.

Funding

Qatar National Library funded the publication of this article.

Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 18 November 2022
DOI 10.3389/fenvs.2022.1065140

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OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Environmental Economics and Management,
a section of the journal Frontiers in Environmental Science

RECEIVED 09 October 2022
ACCEPTED 31 October 2022
PUBLISHED 18 November 2022

CITATION
Dong H, Huang Q, Zhang F, Lu X, Zhang Q, Cao J, Gen L and Li N (2022), Path of carbon emission reduction through land use pattern optimization under future scenario of multi-objective coordination.
Front. Environ. Sci. 10:1065140.
doi: 10.3389/fenvs.2022.1065140

Path of carbon emission reduction through land use pattern optimization under future scenario of multi-objective coordination

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Land use change is one of the crucial factors affecting carbon emissions. The continuously increasing CO_2 and global warming have raised concerns about carbon emission reduction in the process of urbanization. In this research, the Markov and multi-objective optimization models were conducted to predict the demands for land use in Nanjing in 2030 and 2060 under the natural growth (NG) and minimum carbon emission (MCE) scenarios to coordinate the needs of economic development, ecological protection and food security as well as the target of carbon emissions reduction in the future. The spatial distribution of land use simulated by the FLUS (Future Land Use Simulation) model was used to evaluate the effects of future land use on carbon emissions. The results showed that 1) The demands for each type of land use in the NG scenario were significantly different from those in the MCE scenario. Considering the goals of food security and ecological protection in the future, the total amount of cultivated land would not decrease in the MCE scenario, and the area of construction land was significantly smaller than that in the NG scenario. 2) The carbon emissions of Nanjing under the MCE scenario would decrease by 3.94 and 11.80 million tons in 2030 and 2060, respectively, accounting for 9.97% and 27.17% of the total carbon emissions. The optimization of land use patterns can effectively reduce carbon emissions in the process of urbanization.

KEYWORDS

carbon emissions, land use change, FLUS model, multi-objective optimization model, Markov model

1 Introduction

The continuous increase in global CO_2 concentrations and the resulting climate warming have become one of the most severe challenges faced by human society in the 21st century (Tigchelaar et al., 2018). Under the Paris Agreement on climate change, various countries pledged to keep global warming well below 2°C and preferably to 1.5°C compared to pre-industrial levels (Park et al., 2018). The Chinese government announced that China would strive to reach its CO_2 emissions peak by 2030 and achieve carbon neutrality by 2060. Thus, how to reduce carbon emissions has become a main focus of Chinese government.

Land is the carrier of major anthropogenic carbon emissions, and land use effects on carbon emission differ significantly (Chuai et al., 2015b). Land use transitions among different types affect anthropogenic carbon emissions. Previous studies have shown that the cumulative carbon emissions from land use change since 1959 accounted for 19% of global anthropogenic carbon emissions (Friedlingstein et al., 2020). The reasonable planning and layout of limited land resources and the optimization of land use structure can effectively reduce carbon emissions and promote the coordinated development of the socio-economy and eco-environment (Xiao et al., 2007; Chuai et al., 2015a; Wang and Han, 2021). Therefore, research on the carbon emission effects of land use change is of great strategic significance for controlling carbon emissions to achieve carbon neutrality goals.

Land use/land cover change is an important component of global environmental change, land use change simulation plays a key role in analyzing the impacts of land use change for a wide variety of socioeconomic and ecological processes (Liang et al., 2021; Houghton et al., 2012). The cellular automata (CA) model has distinct advantages in dynamically simulating nonlinear complex geospatial systems (Liu et al., 2017; Liang et al., 2021) and has been widely used in the simulation of land use change. Many studies have focused on the transformation rules and parameter optimization of the CA model. The methods have been developed from heuristic or linear methods (e.g., logistic regression (Mirbagheri and Alimohammadi, 2017), grey model (Li and Yeh, 2000)) to intelligent or nonlinear methods (e.g., ant colony algorithm (Liu et al., 2007), ensemble Kalman filter (Zhang et al., 2015), machine learning (Morshed et al., 2022). These studies mainly focus on the simulation of the expansion of construction land and aims to analyze the sprawl of the city. In recent years, the CA model not only was developed to be able to simulate changes of different kinds of land use but also greatly improved the accuracy of simulation by combining with the intelligent algorithm (Li et al., 2017; Liu et al., 2017). As one of the most typical representative of CA model, the FLUS model (Future Land Use Simulation) showed high adaptability in simulating future land use under different scenarios through continuous model improvement (Liang et al., 2018a; Liang et al., 2018b; Liu et al., 2018) and has been widely used in the simulation of land use change (Liang et al., 2018a; Liang et al., 2018b; Zhang D. et al, 2020a; Chen et al., 2020; Liao et al., 2020).

However, less consideration has been given to ecological protection and food security in the simulation of land use change in previous studies (Verburg et al., 2002; Pijanowski et al., 2006; Schaldach et al., 2011). In the context of global greenhouse gas emissions control and China's carbon peak and carbon neutrality goals, how to optimize future land use structure and layout while considering the balance among economic development, ecological protection and food security has become an urgent problem for effectively reducing carbon emissions.

Urbanization level is highly correlated with land use change. Urban expansion necessarily occupy other land use spaces, which results in large amounts of carbon emissions. Since the 1980s, both domestic and international studies have begun to focus on the carbon emission effect of land use change and have found that land use change is one of the dominant factors changing the total amount of CO_2 in the air (Campbell et al., 2000; Watson et al., 2000; Ali and Nitivattananon, 2012). Many studies indicated that the carbon emission effects of land use had remarkable differences from urban (Hutyra et al., 2011; Zhao et al., 2014), regional (Chuai et al., 2016; Li et al., 2020), and national (Leite et al., 2012) to global (Houghton et al., 2012) scales. For example, Zhao et al. (Zhao et al., 2014) explored the optimization of land use structure by using linear programming approach in order to form a low-carbon land use pattern. Cui et al. (Cui et al., 2018) found that the increase in urban land in the Yangtze River Delta urban agglomeration in the past 20 years contributed to approximately half of the total urban carbon emissions. Lai et al. (Lai et al., 2016) considered that the increase in the total amount of carbon emissions in China during 1990–2010 was mainly due to land use conversions among different types. However, current studies have mainly focused on the carbon emission effects of land use structure change, and the effects of different land use transfers spatially are still unclear. The optimization of the layout and structure of future land use and its carbon emission effects still need further research.

In this study, we used both the Markov model and the multi-objective optimization model to forecast the land use demands in Nanjing in 2030 and 2060, and the FLUS model was employed to spatially allocate the land use in the natural growth (NG) and minimum carbon emission (MCE) scenarios. We investigated the differences in land use changes between the two scenarios and quantitatively evaluated the carbon emission effects of land use patterns in the two scenarios. Our results highlight challenges in using the multi-objective optimization model to coordinate the needs of future urban expansion in the constraints of food security, ecological protection and economic development. Additionally, this research provides some possible paths for urban expansion with minimal carbon emissions for the cities of China in the future.

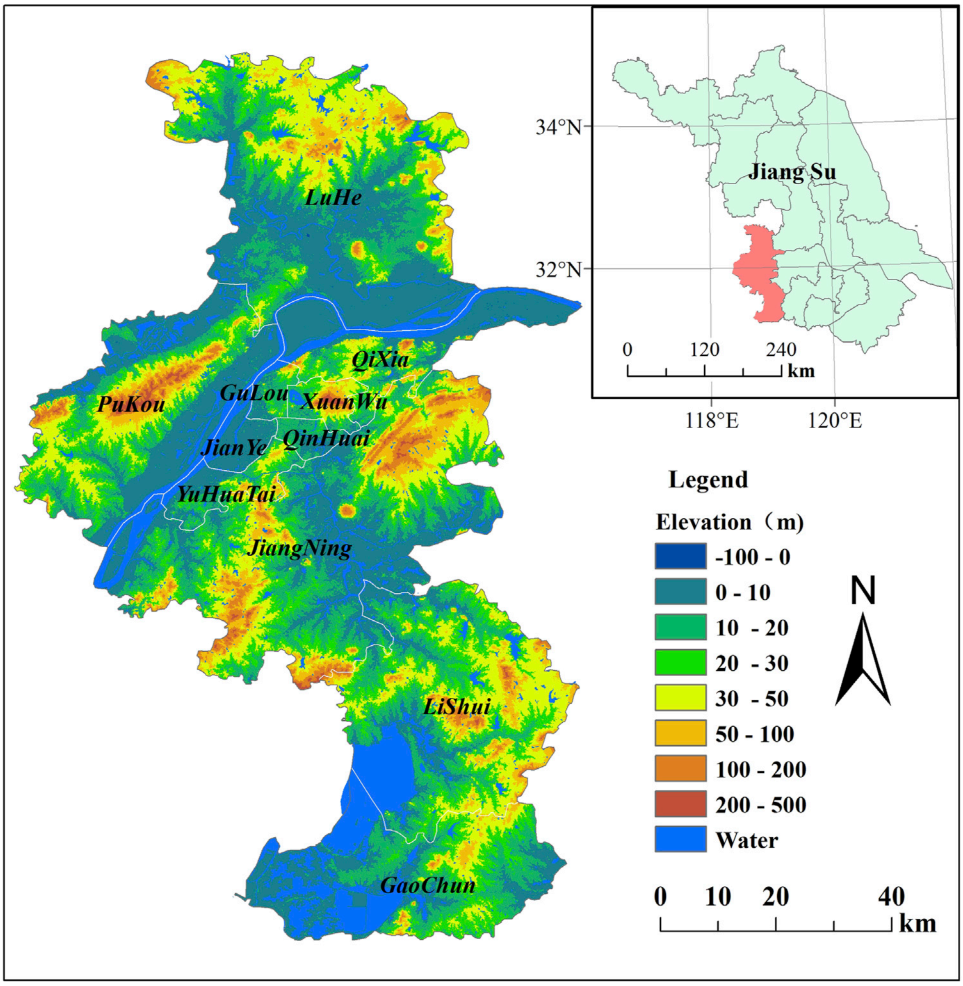

FIGURE 1
The geographic location of Nanjing in Jiangsu province.

2 Materials and methods

2.1 Study area

The study area of Nanjing, Jiangsu Province, with a total land area of approximately 6,587.02 square kilometres, is located at 118°22”~119°14″E, 31°14”~32°37″N. It is an important intersection zone between the Yangtze River economic belt and the “Belt and Road”, which has an important strategic position (Figure 1). According to the data in the Nanjing Statistical Yearbook (http://tjj.nanjing.gov.cn/), Nanjing had a resident population of 9,319,700 and a gross regional product of 148.18 billion CNY in late 2020. And the urbanization rate of Nanjing has increased from 78.5% in 2010 to 86.8% in 2020, Continued reduction of cropland and expansion of construction land in this region have gradually increased the pressure on resources and the environment.

2.2 Data sources

The FLUS model used in this paper was driven by land use data, driving factor data (including topography, transportation data, etc.) and socioeconomic data. The land use data were interpreted from Landsat TM/ETM remote sensing images and obtained from the Resource and Environmental Science Data Center (https://www.resdc.cn/) and were reclassified into seven land use types: cultivated land, woodland, grassland, waters, urban construction land, rural residential land, and unutilized land. The area of each land use type is shown in Figure 2. The transportation factor data were the distances to major roads (including railroads, highways, national roads, provincial roads, and county roads) and distances to city, district, and county centres, which were calculated using Euclidean distance. Other driving factors included topographical factor data, e.g., elevation, slope and aspect, and

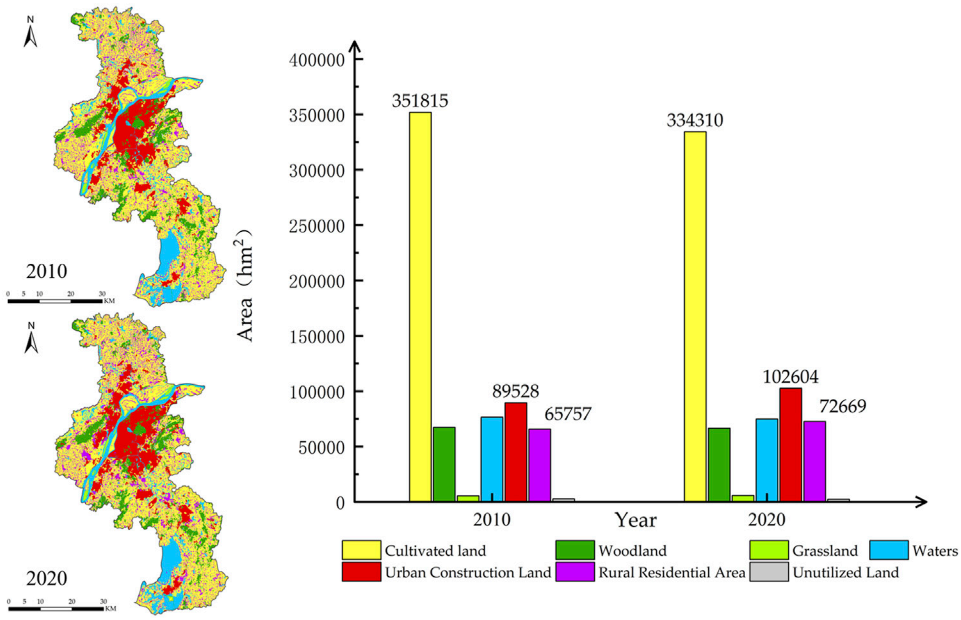

FIGURE 2
The area of each land use type in 2010 and 2020.

population density data. The elevation data were obtained from the Geospatial Data Cloud (http://www.gscloud.cn/), and the slope and aspect data were generated by using terrain analysis tools. The spatial distribution data of population density were obtained from World Pop (https://www.worldpop.org/), and the gridded dataset was generated by remotely-sensed data and geospatial data using Random Forest model. All data were mapped to the interval (0, 1) by the normalization method.

2.3 Methods

In this paper, future urban development scenarios were set up as the natural growth scenario (NG) and the multi-objective collaborative minimum carbon emission scenario (MCE). The Markov model was used in the NG scenario to predict future land use demands based on the trend of the historical period. The multi-objective optimization model was used in the MCE scenario to predict future land use demands under the constraints of food security, ecological protection, and economic development, and the minimization of carbon emissions was used as the objective function to balance different land use demands. Then, the FLUS model was used to simulate the spatial distribution of land use in 2030 and 2060 based on the areas of each land use type under the NG and MCE scenarios. The flowchart of the methods in this study is illustrated in Figure 3.

2.3.1 Markov model

The Markov model, i.e., the Markov chain (Oliveira Barros et al., 2018), based on probability theory, was used to simulate future land use changes in a stochastic state (that is, a shift with a certain probability from one period to another), and this state was related only to the present and not related to the past and future. This model is fit for predicting long-term trends and has been widely used to simulate future land use change (Iacono et al., 2015; Durmusoglu and Akın Tanrıöver, 2017). The probability transfer matrix is the key to this model. The mathematical formulas are as follows:

$$S_{(t+1)} = P_{ij} \times S_t \tag{1}$$

$$P_{ij} = \begin{bmatrix} P_{11} & \cdots & P_{1n} \\ \vdots & \ddots & \vdots \\ P_{n1} & \cdots & P_{nn} \end{bmatrix} \tag{2}$$

where $S_{(t+1)}$ denotes the land use in period t+1, S_t denotes the land use in period t, and P_{ij} is the land use transfer probability matrix, with range values from 0 to 1, i, j = 1,2,3...,n.

2.3.2 Multi-objective optimization model

The multi-objective optimization model was used to predict the future land use demand in Nanjing by considering the constraints of multi-objective demands for food security, ecological protection, and economic development and the minimization of carbon emissions. This model was expressed in mathematical Formula (3), and the optimal solution was

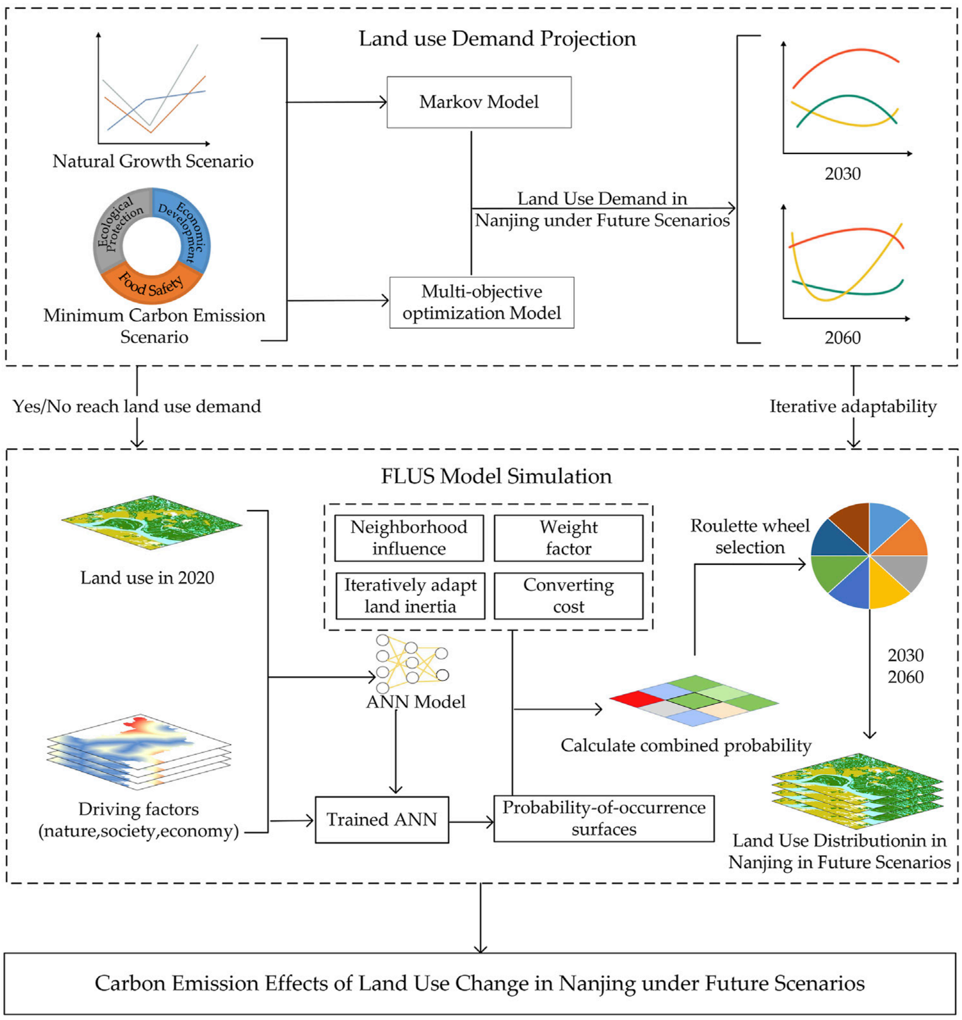

FIGURE 3
The flowchart of methods in this study.

obtained when the value of variable xi met the requirement of the extreme values of the objective function F(X):

$$F(X) = f(x_1, x_2, x_3 \ldots, x_n) \tag{3}$$

The area of seven land use types (i.e., cultivated land X1, woodland X2, grassland X3, urban construction land X4, rural residential land X5, water X6, and unused land X7) were selected as the decision variables. The multi-objective demands on land use of food security, ecological protection, and economic development were set as the constraints, and the minimization of carbon emissions was used to construct the objective function.

2.3.2.1 Multi-objective constraints

(1) Total land area constraint. According to the spatial distribution data of land use in Nanjing in 2010 and 2020, the total land area was approximately 659,051.37 ha. The sum of the land areas of all types should be equal to the total area, which should be unchanged under future scenarios. The constraint equation of the total land area is as follows:

$$\sum\nolimits_{j=1}^{7} X_j = 659051.37,\ \ X_j > 0$$

(2) Cultivated land demand constraint. Considering the demands of land use for food security, the amount of cultivated land in Nanjing should not be reduced in the future. Therefore, the amount of cultivated land in 2020 (334,310.49 ha) was set as the lower limit of the cultivated land demand. Generally, the increment of cultivated land derived from the consolidation of rural settlements and the

reclamation of abandoned industrial and mining land was offset by the occupation of urban construction land. The net increase in cultivated land was mainly derived from the development of unused land. Therefore, from the perspective of maximizing the supplementation of cultivated land, assuming all the unused land would be converted to cultivated land in future scenarios, the summed area of cultivated land and unused land was set as the upper limit of the cultivated land demand. The constraint equation of cultivated land area in Nanjing is as follows:

$$334310.49 \leq X_1 \leq 336737.2$$

(3) Woodland demand constraint. In view of the demand for land use for ecological protection, the amount of woodland in Nanjing should not be reduced in the future. Therefore, the amount of woodland in 2020 (66,464.37 ha) was set as the lower limit of the woodland demand. To match the requirements in carrying out greening programs and enhancing the carbon absorption capacity of ecosystems, which was outlined in the 14th Five-Year Plan (2021–2025) and the Long-Range Objectives through the year 2035 for Nanjing, there should be an increase in the area of woodland in the future. Considering the increased potential of woodland derived from the construction of ecological corridors along the Yangtze River shoreline and traffic arteries and vegetation restoration of mining areas, the average growth rate of the woodland area is expected to be 0.3% in future years, and this value was used as the upper limit of the woodland demand. The constraint equation of woodland area in Nanjing is as follows:

$$66464.37 \leq X_2 \leq 66663.76$$

(4) Grassland demand constraint. The grassland area of Nanjing in 2020 was 5,809.14 ha, accounting for only 0.88% of the total land area. Meanwhile, there was a smaller-magnitude change in the grassland area during 2010–2020, with an average annual change rate ranging from −0.09% to 1.37%. According to the abovementioned change rate range of grassland area, the constraint equation of grassland demand in Nanjing was established as follows:

$$5759.92 \leq X_3 \leq 6655.67$$

(5) Urban construction land demand constraint. With the development of economy, Nanjing should not shrink in size in the future as the capital of Jiangsu Province and the mega-city in the Yangtze River Delta, the current size should be the minimum area of urban construction land in the future. We extrapolated the demand for urban construction land in Nanjing in the future based on the urban resident population and the per capita urban construction land use standards (see Supplementary Table S1). The time series data of the resident population size and urbanization rate in Nanjing from 2000 to 2020, as well as the trend extrapolation method and logistic model were used to predicate the resident population (10.93 million) and urbanization rate (90%) of Nanjing in 2030. And then the urban resident population (multiply of resident population and urbanization rate) was calculated to be 9.837 million in 2030 in Nanjing. According to the per capita urban construction land area (112.38 m^2 per capita) in Nanjing in 2020 and the Urban Land Classification and Planning Construction Land Standard (GB50137-2011), the magnitude of the per capita urban construction land area should reduce by $-15\,m^2$ for the increasing of resident population. Combined with the above calculation and the ratio of urban construction land, the constraint equation for the urban construction land was established as follows:

$$105,516.26 \leq X_4 \leq 118,258.49$$

(6) Rural residential land demand constraint. With the progress of urbanization, a large number of rural populations shift to cities and towns, and there should be a declining trend of rural residential land. The future demand for rural residential land in Nanjing was also extrapolated based on the future rural resident population and the expected per capita rural residential land. Using the above predicted resident population and urbanization rate, we obtained the rural resident population of Nanjing in 2030 (1.093 million). To meet the requirements of new-type urbanization and land use intensification, the rural residential land area and per capita rural residential land in Nanjing should be decreased with the decrease in the rural population. The per capita rural residential land was set to decrease by 10% in 2030, which was used to identify the lower limit of the rural residential land demand. The amount of rural residential land in 2020 (72,669.15 ha) was set as the upper limit, and then the constraint equation of rural residential land was as follows:

$$58129.41 \leq X_5 \leq 72669.15$$

(7) Water demand constraint. The water area of Nanjing in 2020 was 74,768.04 ha, and it had an average annual decrease rate of 0.23% during 2010–2020. The decrease in water was mainly due to the transfer of rural ponds to other lands, but the amount of water change was small. Then, assuming that the future water change would be consistent with the historic change trend, the water area extrapolated by the average annual decrease rate was set as the lower limit, and the water area in 2020 was set as the upper limit of water demand. The constraint equation of the Nanjing water demand was established as follows:

$$73091.51 \leq X_6 \leq 74768.04$$

TABLE 1 Carbon emission parameters of different land use patterns (t/hectare).

Variable	LULC	Carbon emissions factor			
		Lai (2010)	Chuai (2015)	Zhao (2013)	This paper
X_1	Cultivated land	0.50	−0.03	2.24	2.24
X_2	Woodland	0.03	−0.09	0.14	0.14
X_3	Grassland	–	0.02	0	0
X_4	Urban construction land	55.81	202.43	399.84	365.76
X_5	Rural residential land	8.28	27.91	7.22	7.22
X_6	Waters	0.72	−0.12	0.95	0.95
	Research Area	China	Coastal area of Jiangsu	Nanjing	Nanjing

TABLE 2 Neighbourhood factor parameters in FLUS model.

LULC	Neighbourhood factor parameters	LULC	Neighbourhood factor parameters
Cultivated land	0.5	Waters	0.5
Woodland	0.5	Urban construction land	1
Grassland	0.5	Rural residential area	0.1
Unutilized land	0.1		

2.3.2.2 Objective function of carbon emissions minimization

Research on the carbon emission intensity of different land use types has been extensively conducted at the national (Lai, 2010), regional (Chuai et al., 2015b), and urban (Zhao et al., 2013) scales, and related results are shown in Table 1. The values of carbon emission intensity of the different land use types used in the manuscript mainly referenced the results of Zhao et al. (2013) for considering the differences in carbon emission intensity of land use in different regions. Due to the differences in land use classification systems, the carbon emission intensity of urban construction land might be overestimated when incorporating other construction land, such as transportation, into urban construction land. Therefore, the weighted average method was used to adjust the carbon emission intensity of urban construction land. The carbon emission intensity parameters of different land use types in Nanjing are given in Table 1.

Based on the parameters of carbon emissions of each land use type, the objective function of carbon emission minimization in multi-objective collaboration was constructed as follows:

$$\mathrm{Min}(F) = 2.24X_1 + 0.14X_2 + 6.77X_3 + 365.76X_4 + 7.22X_5 + 0.95X_6 \quad (4)$$

Where F is the sum of total carbon emissions generated by different land use types, and X_1, X_2... X_6 are the demand of different land uses. This model was solved by LINGO (Linear Interactive and General Optimizer), an interactive linear and general optimization solver that is widely used to solve linear, nonlinear, and integer optimization models.

2.3.3 FLUS model

In the manuscript, the FLUS model was used to simulate the future spatial distribution of land use in Nanjing, which was improved based on the CA model by Liu et al. (2017). This model considers the effects of human activities and natural factors and can be applied to simulate the spatial changes in land use under historical and future scenarios (Li et al., 2011; Liu et al., 2017; Liu et al., 2018). Based on the spatial distribution of land use and driving factor data in the baseline period (2010, 2020), the backpropagation artificial neural network algorithm (BP-ANN) was employed in the FLUS model to calculate the suitability probabilities of various land types and then to transfer land use types by the roulette method (Zhang et al., 2022). The main calculation modules of the FLUS model are as follows.

(1) BP-ANN-based suitability probability calculation

The ANN algorithm consists of the input and the implicit and output layers and can be formulated as follows:

$$sp(p,\ k,\ t) = sigmoid(net_n(k,\ t)) \times \sum_n w_{n,k} \times \frac{1}{1 + e^{-net_n(k,t)}} \quad (5)$$

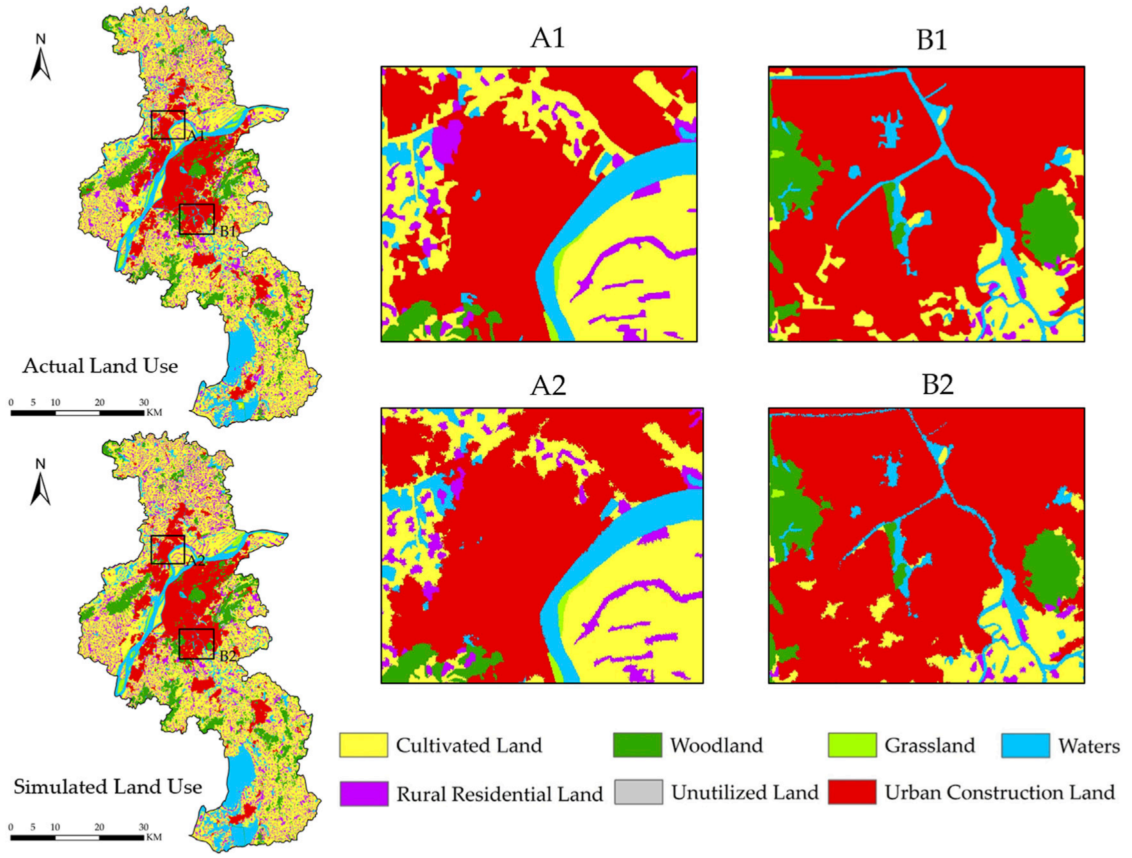

FIGURE 4
Actual and simulated land use patterns in Nanjing in 2020. **(A,B)** represent their respective regions; **(A1, A2)** represent the actual and simulated land use patterns in region **(A)**; and **(B1, B2)** represent the actual and simulated land use patterns in region **(B)**.

where $sp(p, k, t)$ is the suitability probability of land use type k in grid cell p at time t; $w_{n,k}$ is the weight between the hidden layer and the output layer; *sigmoid* is the activation function from the implied layer to the output layer; and $net_n(k,t)$ represents the signal in the nth implied layer received from grid cell p at time t.

The sum of suitability probabilities for all types of land use in the BP-ANN algorithm was 1, i.e.,

$$sp(p, k, t) = 1 \tag{6}$$

The training samples were randomly selected by ANN. The sampling proportion was set to 20%, and the number of hidden layers was empirically set to 12. The suitability probabilities of different land use types were obtained by inputting the normalization of all driver factor raster data into the FLUS model.

(2) Self-adaptive inertia and competition mechanism

The core of the self-adaptive inertia mechanism in the FLUS model is the inertia coefficient, which is adjusted based on the differences between the actual distribution and the expected demand of different land uses to achieve the predetermined targets of the amount of land use. The formula was defined as follows:

$$I_k^t = \begin{cases} I_k^{t-1} & if\left|D_k^{t-1}\right| \le \left|D_k^{t-2}\right| \\ I_k^{t-1} \times \dfrac{D_k^{t-2}}{D_k^{t-1}} & if D_k^{t-1} < D_k^{t-2} < 0 \\ I_k^{t-1} \times \dfrac{D_k^{t-1}}{D_k^{t-2}} & if 0 < D_k^{t-2} < D_k^{t-1} \end{cases} \tag{7}$$

where I_k^t denotes the inertia coefficient of land use type k at time t, and D_k^{t-1}、D_k^{t-2} denotes the area difference between the number of grid cells and the demand at times t-1 and t-2.

After calculating the total suitability probability in the ANN model, each land use type was allocated to each cell through several iterations of the CA model. The overall conversion probability in the occupied cells of a specific land type was estimated by using the following equation:

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TABLE 3 Transition matrix of land use types in Nanjing from 2010 to 2020.

Unit/km^2	CL	WL	GL	UC	RR	WA	UL
CL	3,283.85	8.10	0.17	122.83	90.58	12.45	0.18
	3,316.19	6.18	2.40	111.46	81.93	0.00	0.00
WL	7.99	652.11	0.19	6.89	4.62	1.04	0.25
	4.96	655.77	0.00	12.04	0.31	0.00	0.00
GL	0.24	0.12	52.19	0.94	0.26	0.85	0.00
	0.13	0.05	54.16	0.02	0.00	0.24	0.00
UC	8.84	1.62	0.04	882.12	1.03	1.57	0.06
	0.99	0.99	0.20	892.44	0.66	0.00	0.00
RR	27.68	1.41	0.08	2.40	624.63	1.33	0.03
	13.47	0.34	0.02	0.16	643.58	0.00	0.00
WA	14.31	1.01	5.42	8.18	5.56	730.42	0.02
	7.46	0.40	1.04	8.41	0.18	747.44	0.00
UL	0.20	0.27	0.00	2.68	0.01	0.01	23.73
	0.18	0.92	0.00	1.50	0.03	0.00	24.27

Note: the upper row of each land use type in the matrix is the actual situation, and the lower row is the simulated situation presented in italics. CL, cultivated land; WL, woodland; GL, grassland; WA, water; UC, urban construction land; RR, rural residential land; UL, unutilized land.

$$TP_{p,k}^{t} = sp(p,k,t) \times \Omega_{p,k}^{t} \times I_k^t \times (1 - sc_{c\to k}) \tag{8}$$

where $TP_{p,k}^{t}$ is the overall probability of conversion to type k of cell p at time t; $sp(p, k, t)$ is the probability of suitability of cell p to type k; $\Omega_{p,k}^{t}$ denotes the neighbourhood influence factors; I_k^t is the self-adaptive inertia coefficient; $sc_{c\to k}$ is the conversion costs from type c to type k; and $\Omega_{p,k}^{t}$ is the neighbourhood influence (Zhang X. R. et al., 2020b) and is expressed as follows:

$$\Omega_{p,k}^{t} = \frac{\sum_{N\times N} con\left(c_p^{t-1} = k\right)}{N \times N - 1} \times w_k \tag{9}$$

where $\sum_{N\times N} con(c_p^{t-1} = k)$ denotes the number of cells of type k in the N×N window after the last iteration, and w_k denotes the parameters of the neighbourhood factors of different land types (Cao et al., 2019), with a range of values from 0 to 1.

In this study, a 3 × 3 window-based neighbourhood was used, and the number of iterations was set to 300. The parameters of the neighbourhood factors of each land type outlined in Table 2 were set based on the future development trend.

Kappa coefficients were used to verify the simulation accuracy by comparing the actual distributions of land use in 2020 with the simulated results with 2010 as the base year. The expression of Kappa was as follows:

$$Kappa = \frac{p_o - p_c}{p_p - p_c} \tag{10}$$

where p_o is the ratio of the number of correctly simulated cells to the total number of cells, i.e., the correct rate of simulation; p_c is the expected correct rate of simulation in the random state, and the value in this study was set to 1/7 considering seven land types; and p_p is the ratio of the number of correctly simulated cells to the total number of cells in the ideal state, with a value as 1.

3 Results

3.1 Accuracy verification of the FLUS model

The FLUS model simulated spatial distributions of land use in Nanjing in 2020 by using 2010 as the base year, and the results were verified against the actual situation for accuracy. The

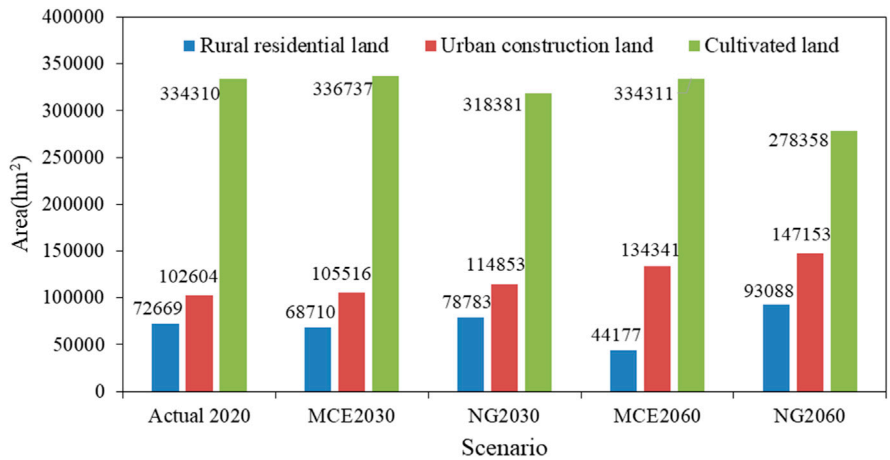

FIGURE 5
The demand for each land use type in Nanjing in 2030 and 2060 under future scenarios (hectare).

TABLE 4 The area of land use of each type in Nanjing under future scenarios (hectare).

LULC	Actual situation	Land use demand in the MCE scenario		Land use demand in the NG scenario	
	2020	2030	2060	2030	2060
CL	334310.49	336737.2	334310.5	318380.76	278357.67
WL	66464.37	66663.76	66663.76	65641.14	63293.58
GL	5,809.14	6,655.67	5,759.92	6,098.94	6,948.18
WA	74768.04	74768.04	73798.82	73100.07	68431.05
UC	102603.51	105516.3	134341.1	114853.05	147153.06
RR	72669.15	68710.44	44177.28	78783.03	93087.54
UL	2,426.67	0	0	2,194.38	1780.29

comparative results indicated that the simulated spatial distributions of land use had good agreement with the actual situation, with a high simulation accuracy of 0.91 (shown in Figure 4), which met the needs of land use simulation. Additionally, the conversions of cropland to urban construction land and rural residential land were the two main transfer paths (shown in Table 3), of which the simulation errors compare with the actual situations were 9.25% and 9.54%, respectively. The FLUS model had good adaptability in this study.

3.2 Land use demand in nanjing in future scenarios

The demand for type of land use in Nanjing in 2030 and 2060 in the NG scenario was significantly different from that in the MCE scenario, as shown in Figure 5 and Table 4. In the NG scenario, compared with 2020, the area of cultivated land decreased by 4.76% and 16.74%, whereas the area of urban construction land increased by 11.94% and 43.42%, and the area of rural residential land increased by 8.41% and 28.10% in 2030 and 2060, respectively. In the MCE scenario, the area of cultivated land decrease less than 1%, the rural residential land also decreased by 5.45% and 18.40%, and the urban construction land increased slightly by 1.53% and 12.28% in 2030 and 2060, respectively.

3.3 Spatial distribution of land use in nanjing under future scenarios

Based on the actual situation of land use and driving factor data in 2020 and the predicted land use of each type in the NG and MCE scenarios, the respective spatial distributions of land use in Nanjing in 2030 and 2060 simulated by the FLUS model are shown in Figure 6. Although the land use patterns in the NG and MCE scenarios were approximately similar, the scale of construction land expansion in the NG scenario was larger than that in the MCE scenario. Additionally, there were some differences in the method of construction land expansion in the two scenarios, as shown in Figure 7. In the NG scenario, the urban construction land expanded outward along the current urban boundary, resulting in the occupation of a large amount of cultivated land. In contrast, in the MCE scenario, the expansion of urban construction land mainly came from the scattered rural residential land surrounding the urban boundary.

3.4 Land use changes in nanjing in future scenarios

According to the actual spatial distribution of land use in 2020 and the simulated spatial distribution of land use in 2030 and 2060 in the NG and MCE scenarios, Sankey diagrams of the land transfer matrix of Nanjing in 2020–2030 and 2020–2060 in the two scenarios were established, as shown in Figure 8. Overall, the land use structure of Nanjing in future scenarios was relatively stable. The area of cultivated land was the largest, accounting for approximately 50%–51% of the total land area, and the area of urban construction land was the second largest, accounting for approximately 15%–17%. The proportions of rural residential land, water and woodland were all approximately 10%, and the area of grassland and unused land was relatively small.

However, the transfer paths of land use in Nanjing in the different scenarios differed significantly. In the MCE scenario, the conversions of rural residential land, cultivated land, and unutilized land to urban construction land were the main paths of land use transfer from 2020 to

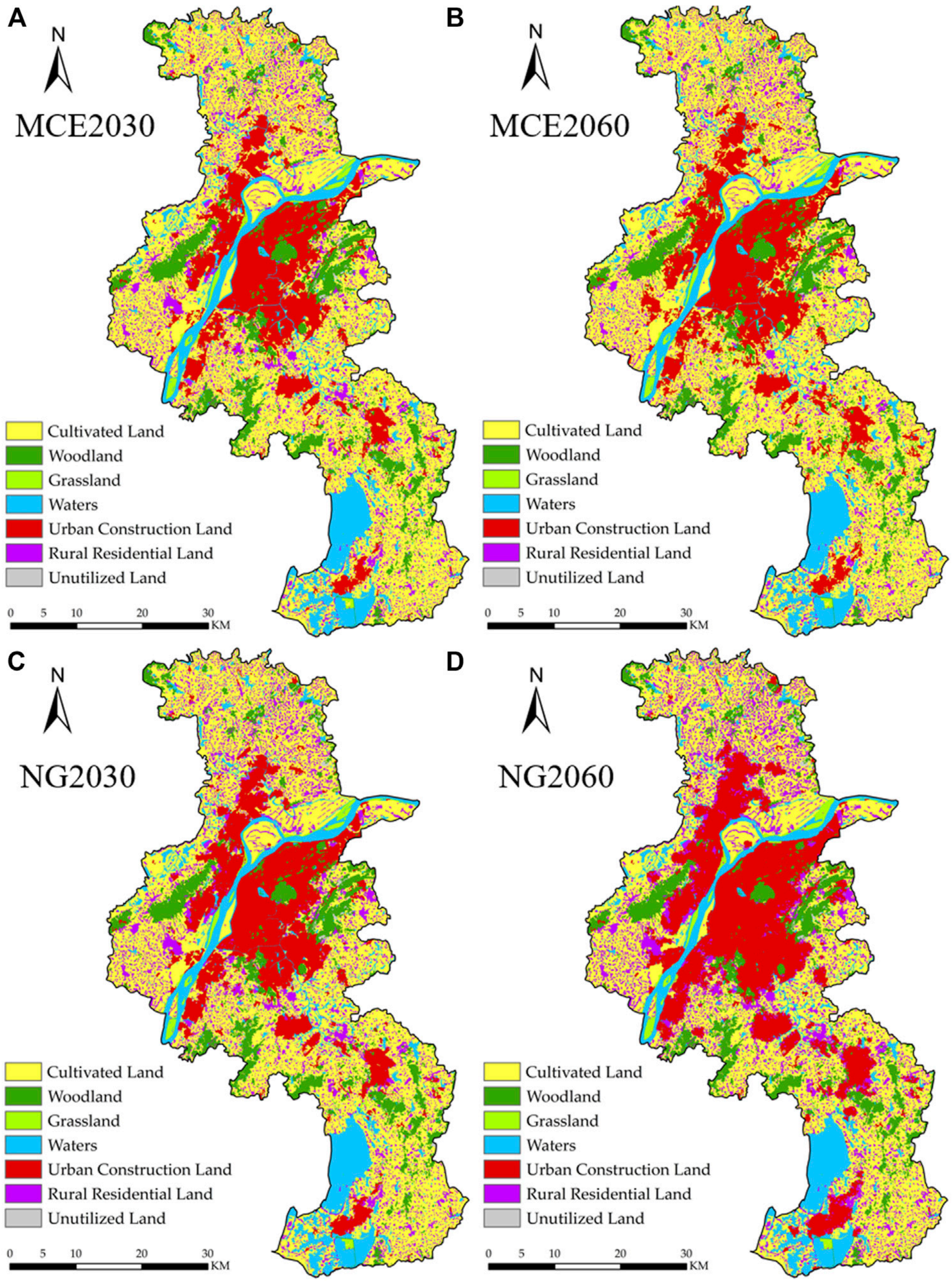

FIGURE 6
Spatial distribution of land use in Nanjing in 2030 **(A,C)** and 2060 **(B,D)** in the NG **(C,D)** and MCE **(A,B)** scenarios.

2030, where rural residential land transfer accounted for 65.66% of the total area transferred to urban construction land. Furthermore, during the period 2020–2060, the conversion of rural residential land to urban construction land was the more dominant path of land use transfer, with a proportion of 90.71% of the total area transferred to urban construction land. Additionally, the interconversions between cultivated land, rural residential land and waters were very active. Compared with the MCE scenario, the interconversions between different land use types were

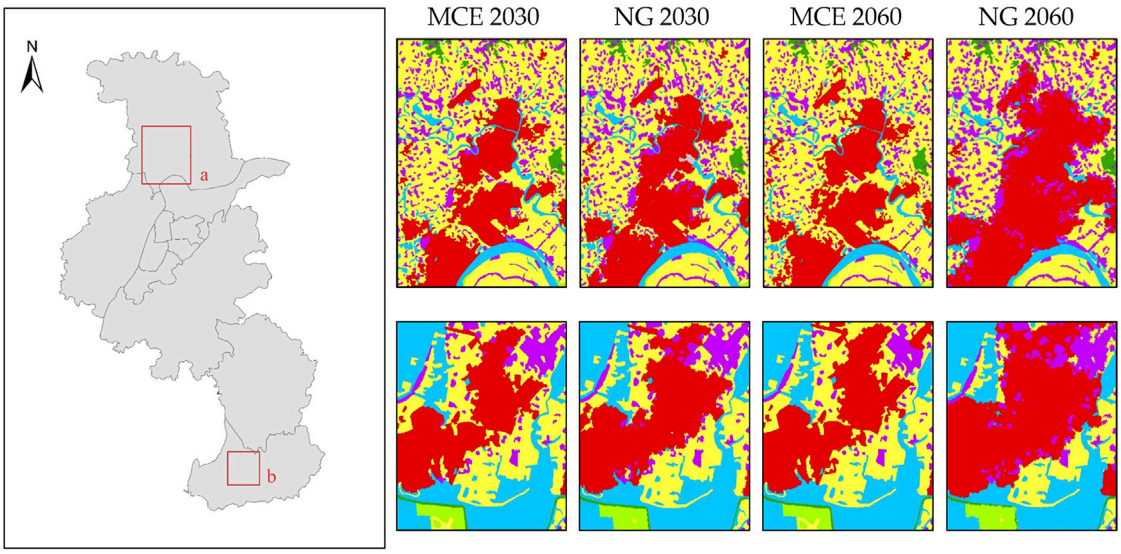

FIGURE 7
Two enlarged views of land use simulation in 2030 and 2060 in the NG and MCE scenarios.

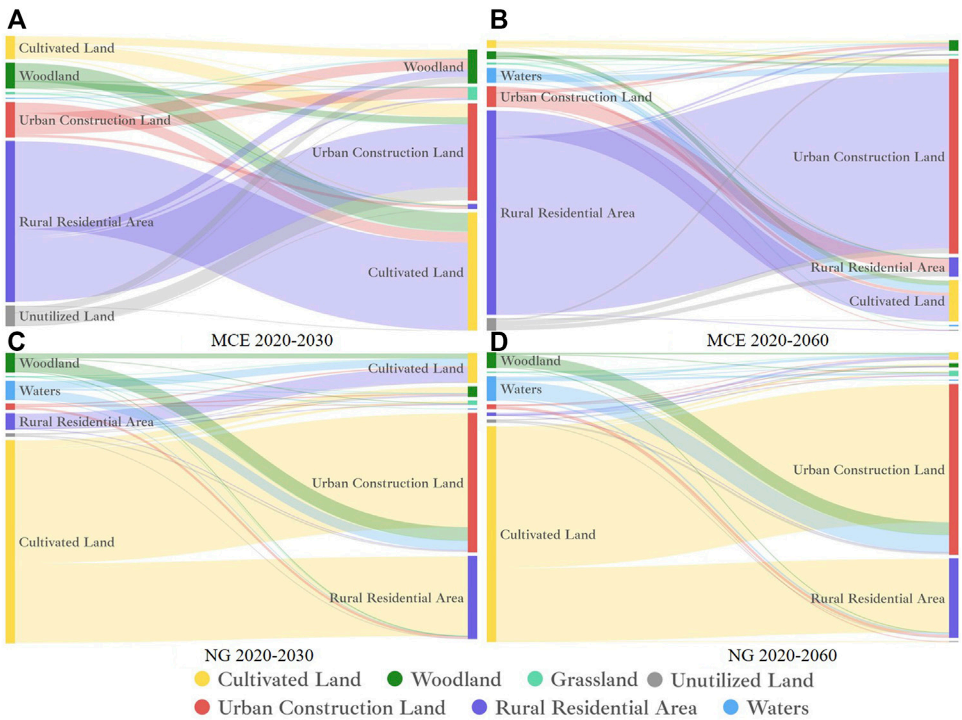

FIGURE 8
Sankey diagrams of land transfer matrix of Nanjing during 2020–2030 **(A,C)** and 2020–2060 **(B,D)** in the NG **(C,D)** and MCE scenarios **(A,B)**.

remarkably different in the NG scenario because no constraints were set on land use change. The significant characteristics of land use transfer in the NG scenario were that the area of cultivated land decreased considerably due to the urban construction land expansion, and a large area of woodland was also converted to urban construction land.

TABLE 5 Carbon emissions from different land uses in Nanjing in 2030 and 2060 under different scenarios.

Land use type		In the NG scenario		In the MCE scenario	
		Area (hm^2)	Carbon emissions (10^4t)	Area (hm^2)	Carbon emissions (10^4t)
CL	2030	318380.76	71.32	336737.79	75.43
	2060	278357.67	62.35	336740.67	75.43
WL	2030	65641.14	0.92	66663.72	0.93
	2060	63293.58	0.89	66663.72	0.93
GL	2030	6098.94	4.13	6082.11	4.12
	2060	6948.18	4.70	5759.91	3.90
WA	2030	73100.07	6.94	74768.04	7.10
	2060	68431.05	6.50	73798.83	7.01
UC	2030	114853.05	4200.87	104168.97	3810.08
	2060	147153.06	5382.27	115202.97	4213.66
RR	2030	78783.03	56.88	68710.41	49.61
	2060	93087.54	67.21	59294.52	42.81
UL	2030	2194.38	0.00	1920.33	0.00
	2060	1780.29	0.00	1590.75	0.00

TABLE 6 Carbon emissions of land use change in Nanjing during the periods of 2020–2030 and 2020–2060 under the MCE scenario.

Carbon emissions Change/10^4 t	CL	WL	GL	WA	UC	RR	UL
CL	0.00	−0.04	0.00	0.00	12.29	0.01	0.00
	0.00	−0.03	0.00	0.00	11.51	0.01	0.00
WL	0.10	0.00	0.00	0.00	6.23	0.00	0.00
	0.07	0.00	0.00	0.00	6.11	0.00	0.00
GL	−0.01	−0.01	0.00	0.00	0.07	0.00	0.00
	0.00	-0.01	0.00	−0.03	0.36	0.00	0.00
WA	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.07	0.00	0.02	0.00	16.14	0.00	0.00
UC	−4.78	−4.22	−1.53	0.00	0.00	−7.48	0.00
	-8.33	-8.15	-0.07	0.00	0.00	−35.19	0.00
RR	−1.11	−0.13	0.00	0.00	57.45	0.00	0.00
	−0.91	−0.11	0.00	0.00	456.48	0.00	0.00
UL	0.00	0.00	0.00	0.00	12.00	0.00	0.00
	0.00	0.00	0.00	0.00	13.41	0.24	0.00

Note: The time interval of the upper row of each land use type in the matrix is 2020–2030 and that in the lower row is 2020–2060.

3.5 Carbon emission effects of land use change in nanjing under future scenarios

The carbon emission effects of land use in Nanjing in 2030 and 2060 using the coefficients of carbon emissions of each land use type are shown in Table 5. Under the NG scenario, the carbon emissions from land use in Nanjing in 2030 and 2060 were 43,410,600 tons and 55,239,200 tons, respectively, where the carbon emissions from urban construction land were the largest, up to 42,008,700 tons and 53,822,700 tons in 2030 and 2060, respectively, accounting for 96.77% and 97.43% of the total carbon emissions. The carbon emissions generated by woodland were minimal, with amounts of 9,200 tons and 8,900 tons in 2030 and 2060, respectively. In contrast, under the MCE scenario, the carbon emissions of land use in Nanjing in 2030 and 2060 were 39,472,800 tons and 43,437,500 tons, respectively, where urban construction land was still the land use type with the largest carbon emissions, with amounts of

TABLE 7 Carbon emissions of land use change in Nanjing during the periods of 2020–2030 and 2020–2060 under the NG scenario.

Carbon emissions Change/10^4 t	CL	WL	GL	WA	UC	RR	UL
CL	0.00	−0.13	0.10	0.00	380.01	3.64	0.00
	0.00	−0.13	0.18	0.00	1342.62	9.84	0.00
WL	0.10	0.00	0.00	0.00	45.02	0.02	0.00
	0.09	0.00	0.02	0.00	124.27	0.14	0.00
GL	−0.01	0.00	0.00	−0.01	0.08	0.00	0.00
	0.00	−0.01	0.00	−0.04	0.09	0.00	0.00
WA	0.09	0.00	0.03	0.00	32.07	0.01	0.00
	0.08	0.00	0.33	0.00	171.27	0.28	0.00
UC	−4.78	−4.22	−1.53	0.00	0.00	−7.48	0.00
	−2.68	−3.31	−7.99	0.00	0.00	−24.59	−0.03
RR	−0.68	−0.02	0.00	0.00	2.24	0.00	0.00
	−0.30	−0.02	0.00	0.00	2.22	0.00	0.00
UL	0.00	0.00	0.00	0.00	4.35	0.00	0.00
	0.00	0.00	0.00	0.00	19.42	0.02	0.00

Note: same as in Table 6.

38,100,800 tons and 42,136,600 tons in 2030 and 2060, accounting for 96.52% and 97.01% of the total carbon emissions.

Although the proportion of carbon emissions from urban construction land to total carbon emissions did not change significantly under the two scenarios, the total carbon emissions in the MCE scenario in 2060 increased by only 3,964,700 tons compared to that in 2030, while that in the NG scenario increased by 11,814,000 tons. The total carbon emissions from urban construction land in Nanjing in 2030 and 2060 in the MCE scenario were 3,937,800 tons and 11,801,700 tons less than those in the NG scenario, respectively.

The carbon emissions effects of different land use transfers in Nanjing in 2030 and 2060 under the NG and MCE scenarios are shown in Tables 6, 7. In the MCE scenario, the carbon emissions from land use change in Nanjing by 2030 increased slightly, where the carbon emissions from the conversion of rural residential land to urban construction land were approximately 574,500 tons. By 2060, the increment of carbon emissions from the conversion of rural residential land to urban construction reach 4,564,800 tons. In contrast, the main land use type transferred to urban construction land in the NG scenario was cultivated land, from which the increment of carbon emissions reached 3.801 million tons and 13.4262 million tons in 2030 and 2060, respectively.

4 Discussion

4.1 Comparison of simulation results under different scenarios

The simulated structure and spatial distributions of land use in Nanjing in 2030 and 2060 showed that the urban construction land and rural residential land continued to increase and the cultivated land decrease considerably in the NG scenario, whereas in the MCE scenario, the cultivated land was protected effectively due to the constraint of land use in food security, the growth of urban construction land was slower and the rural residential land did not increase instead decrease. Additionally, in the NG scenario the expansion of urban construction land mainly came from the conversion of cultivated land and woodland, whereas in the MCE the expansion of urban construction land mainly came from rural residential land and the cultivated land changed slightly. Compared with in the NG scenario, the demand for each type of land use in the MCE scenario contributed more to the coordination of economic development with resource conservation and environmental protection to meet the needs of sustainable development.

4.2 The optimization of land use pattern for the reduction of carbon emissions

The areas of cultivated land, woodland, water, and unused land in Nanjing during 2010–2020, showed decreasing trends to different degrees, while the areas of urban construction land, rural residential land and grassland showed increasing trends. In the past 10 years, China has experienced rapid urbanization, and the conversion of cultivated land to urban construction land has been the main path of urbanization development. However, with the proposal of the food security strategy, the protection of cultivated land protection is strengthening, so the probability of the conversion of cultivated land to other land types should decrease in the future. Additionally, according to the requirements of new-type urbanization and land use intensification, the area of rural residential land in Nanjing should significantly decrease in the future. Furthermore, with the enhancement of environmental protection and the carbon neutral target, woodland, as one of the most important carbon sinks in terrestrial ecosystems, should gradually increase. For above reasons, it is unlikely to predict the future land use based on the change trend of the past 10 years, which was inconsistent with the future goals of food security and ecological protection, and the predicted land use in the MCE scenario was more reasonable. And the carbon emissions of land use in the MCE scenario could be effectively reduced in the future.

5 Conclusion

In this paper, the Markov model and the multi-objective optimization model were used to predict the future land use demand in Nanjing under the NG and MCE scenarios, respectively, and the FLUS model was used to simulate the spatial distribution of land use in Nanjing under the two scenarios in 2030 and 2060. Based on the above results, the carbon emissions effects of land use changes under the different scenarios were analysed, and the following conclusions were obtained.

(1) Nanjing has experienced rapid urbanization in the past 10 years, and a large amount of cultivated land has been converted to urban construction land during this period. The area of cultivated land predicted in the NG scenario continued to decrease, and the area of urban construction land and rural residential land continued to increase, which was inconsistent with sustainable development goals, including food security and ecological protection. The estimation of land use demand based on the multi-objective optimization method can balance the needs of future urban development under the constraints of food security, ecological protection, and economic development. Under this condition, the cultivated land was protected, and the expansion scale of construction land was effectively controlled.
(2) The total carbon emissions from land use change in Nanjing predicted in the MCE scenario were much less than those in the NG scenario. Thus, the optimization of land use structure and spatial distribution can effectively reduce carbon emissions in future economic development and is an important path to help achieve the carbon peaking and carbon neutrality goals of China (Figure 1).

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

QH, HD, and FZ contributed to conception and design of the study. HD, GL, and JC organized the database. QH, FZ, HD, and XL performed the statistical analysis. QH and JC performed the visualization. QH and HD wrote the first draft of the manuscript. QH, FZ, XL, QZ, and NL wrote review and editing. All authors contributed to manuscript revision, read, and approved the submitted version.

Funding

This study was funded by the National Natural Science Foundation of China (Grant no. 41871334), the Natural Science Foundation of Jiangsu Province (Grant number. BK20201121), the Key Subject of Ecology of Jiangsu Province (Grant number. SJYH202202), and the Natural Science Foundation of Nanjing Xiaozhuang University (Grant number. 2020NXY15).

Acknowledgments

We really appreciate the editors and anonymous reviewers for their meaningful comments for improving our manuscript.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.1065140/full#supplementary-material

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frontiers | Frontiers in Environmental Science

TYPE Hypothesis and Theory
PUBLISHED 25 November 2022
DOI 10.3389/fenvs.2022.1067835

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OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Environmental Economics and Management,
a section of the journal Frontiers in Environmental Science

RECEIVED 12 October 2022
ACCEPTED 15 November 2022
PUBLISHED 25 November 2022

CITATION
Li Y and Zhang Y (2022), Spatial-temporal evolution and influencing factors of tourism eco-efficiency in China's Beijing-Tianjin-Hebei region.
Front. Environ. Sci. 10:1067835.
doi: 10.3389/fenvs.2022.1067835

Spatial-temporal evolution and influencing factors of tourism eco-efficiency in China's Beijing-Tianjin-Hebei region

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Tourism eco-efficiency is an important index to measure the sustainable development of the tourism industry. The super-SBM (slacked-based measure) model based on undesired output, geographical spatial analysis method, and panel Tobit regression model were used to explore the spatial-temporal evolution characteristics of tourism eco-efficiency and its influencing factors on 13 cities in China's Beijing-Tianjin-Hebei region from 2010 to 2019. The results reveal that: 1) During the study period, high-efficiency cities were mainly in Beijing, Tianjin, and their surrounding areas, and the number of these cities did not change, whereas low-efficiency areas were farther away from central cities, and the number of these cities increased earlier but decreased later. 2) The tourism eco-efficiency in the Beijing-Tianjin-Hebei region exhibits significant positive spatial autocorrelation characteristics, and the driving effect of the spatial radiation of high-efficiency cities on low-efficiency cities in the urban agglomeration is more obvious. 3) The levels of economic development, tourism industry structure, urbanization, and technological progress have a greater impact on tourism ecological efficiency.

KEYWORDS

tourism eco-efficiency, spatial and temporal evolution, influencing factors, Beijing-Tianjin-Hebei, DEA (Data Envelopment Analysis)

1 Introduction

Tourism has experienced significant growth over the last few decades and has become one of the largest economic sectors in the world (Candia and Pirlone, 2022). Tourism development is directly relevant to achieving economic growth and happiness, as well as eliminating poverty. For a long time, tourism has been considered an environmentally friendly industry with low energy consumption, low emission, and low pollution. However, as the scale of the tourism industry continues to grow, it causes serious ecological and environmental problems (Wang et al., 2021). For instance, an increase in the scale of the tourism industry increases energy consumption, sewage discharge, and garbage generation because of the large-scale off-site activities of tourists (Yang and Yang, 2019), thereby imposing great ecological risk (Ruan et al., 2019). Green development concentrate on rational utilization of resources and energy, moderate economic and social development, mutual balance of loss compensation, and harmonious coexistence between human and nature (Jiang and Xiang, 2013). Therefore, tourism development needs to follow a green development path, considering its impact on the ecological environment (Paiano et al., 2020). Previous studies have demonstrated that tourism eco-efficiency can comprehensively reflect the coordinated development level of tourism economic activities and the ecological environment, and it is an important indicator that has often been applied to measure the quality of green tourism development (Gössling et al., 2005; Yao and Chen, 2016; Peng et al., 2017).

Beijing-Tianjin-Hebei region are located in the heart of China's Bohai Sea Rim. It is the largest and most dynamic economic region in northern China, with abundant tourism resources. As a major national strategy, the strategy of Coordinated Development of the Beijing-Tianjin-Hebei Region brings new opportunities to the tourism development and plays an important role in promoting the coordinated development of tourism within the Beijing-Tianjin-Hebei region. However, different geographical locations and economic bases have created the unbalanced development trend of tourism. Beijing and Tianjin have a long history and cultural resources and a solid foundation for tourism. Under the strategic Beijing-Tianjin-Hebei collaborative development, Hebei Province is actively promoting the integration of "tourism +" deepening cooperation in the field of public services and focusing on promoting the integration of transportation, ecology, and the tourism industry. Tourism is an industry that promotes green development in the Beijing-Tianjin-Hebei region, but its high-speed development has also caused a series of environmental problems, such as an imbalance between tourism economic growth and ecological environmental protection as well as having a negative impact on the ecological environment (Ozturk et al., 2016; Sun et al., 2020). Therefore, it is of great significance to explore the spatial-temporal evolution characteristics and influencing factors of tourism eco-efficiency in the Beijing-Tianjin-Hebei region for realizing sustainable tourism development.

This study adopts the super-efficiency SBM model to measure the tourism eco-efficiency in the Beijing-Tianjin-Hebei region from 2010 to 2019 and then conducts exploratory spatial analysis to determine its spatial-temporal evolution characteristics. Moreover, it analyzes the influencing factors using the Tobit regression model. The contribution of this study lies in the following three areas: first, we constructed the index system of tourism eco-efficiency, considering undesired output. Second, we chose 13 cities in the Beijing-Tianjin-Hebei as the empirical research objet to analyze tourism eco-efficiency, which enriches relevant research at the level of prefecture-level cities. Third, combined with exploratory spatial analysis and ArcGIS technology, we accurately demonstrate the tourism eco-efficiency of different cities from static and dynamic levels, which provides reference to make the corresponding ecological strategy for the tourism sustainable development and promote the high-quality economic development in the Beijing-Tianjin-Hebei region.

The remainder of this study is organized as follows. Section 2 presents a literature review on the tourism eco-efficiency. Section 3 introduces the research methods, including the Super-SBM model and panel Tobit regression model. Section 4 provides the results and discussion. Section 5 presents conclusions based on the empirical results and provides some policy implications.

2 Literature review

Research on tourism eco-efficiency mainly focuses on the concept, measurement, influencing factors, countermeasures, and suggestions for promoting tourism eco-efficiency. The concept of tourism eco-efficiency was proposed by Gössling et al. (2005). He calculated the tourism eco-efficiency in the Rocky Mountains, France, Amsterdam, Siena, and other places using carbon dioxide emission and income index and indicated that eco-efficiency is a useful concept for analyzing the combined environmental and economic performance of tourism. Later, Karadayi and Isik (2018), Yao and Chen (2015), Ma and Liu (2016), and other scholars discussed the concept of tourism eco-efficiency. They pointed out that tourism eco-efficiency is an important index for measuring the proportional relationship between the benefits of tourism development and the environmental impacts to achieve "minimum resource input and environmental damage, maximum economic and social output."

Previous studies have proposed a number of different approaches to the assessment of eco-efficiency (Kytzia et al., 2011). The single-ratio method and data envelopment analysis (DEA) method are two important analysis methods for assessing tourism eco-efficiency. Liu et al. (2019) used the single-ratio method to measure the tourism eco-efficiency value of various regions in China; Perch-Nielsen et al. (2010) used the added value of tourism to characterize the economic value of tourism and measured the eco-efficiency of tourism in Switzerland using the single-ratio method. However, the single ratio method, in which tourism eco-efficiency is represented by the ratio of tourism environmental impact and tourism income, is not sufficient to measure regional tourism eco-efficiency (Huang et al., 2014).

In recent years, scholars have analyzed tourism eco-efficiency by DEA method. DEA is a nonparametric tool for eco-efficiency assessment, DEA users do not need to unify the units, consider the functional form, pre-estimate the model parameters, and make a distributional assumption (Lampe and Hilgers, 2015). With the improvement, the DEA model, super-efficiency model, three-phase DEA model, and bootstrap DEA model has been widely used in the measurement of tourism eco-efficiency. Liu et al. (2017) measured the tourism eco-efficiency of 53 coastal cities in China by DEA method, and used the Tobit model to analyze the factors affecting the tourism eco-efficiency of coastal areas. Wang et al. (2021) used the undesirable SBM-DEA model to estimate the tourism eco-efficiency of 31 provinces in China from 1997 to 2016 and analyzed the spatial-temporal evolutionary trends of eco-efficiency in China using the hot spot model and spatial center of gravity model. Song and Li (2019) used the traditional DEA and bootstrap-DEA methods to evaluate the efficiency of China's tourism industry from the perspective of sustainable development and found the key factors and the best path for the sustainable development of tourism under the constraints of environmental protection. Sun and Hou (2021) measured the tourism eco-efficiency of 41 cities in the Yangtze River Delta and explored the spatial network structure and evolution trend of tourism eco-efficiency with a modified gravity model and social network analysis method. Chen et al. (2020) evaluate the regional eco-efficiency and tourism economic development level of China's 30 provinces and cities by using the super-efficiency DEA model and the grey entropy weight method. These achievements use DEA method to measure tourism eco-efficiency, but most of them mainly discussed in the national region and Yangtze River Economic Belt, while there is little literature on the Beijing Tianjin Hebei region.

Furthermore, some scholars discussed influencing factors of tourism eco-efficiency. The main influencing factors of regional tourism eco-efficiency are technical level, economic development level, traffic accessibility, industrial structure, urbanization and environmental regulation factors (Chen et al., 2020; Li et al., 2022). The same views are held by other scholars, such as Liu et al. (2021), who studied the determinants of tourism eco-efficiency of 30 provinces in China, pointed out that the level of economic development, traffic conditions, the professional level of tourism, and openness degree can significantly promote tourism efficiency. An empirical study conducted by Zhang et al. (2022) also indicates that urbanization plays a great role on tourism eco-efficiency.

Summarizing the above literature, it can be observed that research on tourism eco-efficiency has achieved fruitful results, but it is still limited. On the one hand, there has been insufficient attention to the regional tourism eco-efficiency of Beijing-Tianjin-Hebei in China, and hardly discusses tourism eco-efficiency of regional tourism at city level. On the other hand, traditional DEA model and undesired SBM-DEA model were used, which are unable to further distinguish decision making unit, resulting in a deviation of the efficiency value, so the research method needs to be improved. Because of this, this paper utilizes a non-radial super-SBM model and the spatial correlation analysis method to respectively discuss 2010–2019 tourism eco-efficiency. The panel Tobit model is employed to explore the influencing factors on tourism eco-efficiency in the Beijing-Tianjin-Hebei region.

3 Research methods

3.1 Models

3.1.1 Super-SBM model

The SBM-DEA model is based on slacked variables, which directly incorporates the slacked variables into the objective function not only to the benefit ratio but also to maximize the actual profit. However, the SBM model cannot distinguish the size of decision units when the efficiency value is 1. To solve this problem, Andersen and Petersen (1993) proposed the super-efficiency model in 1993. Later, based on the SBM model and the super-efficiency model, Tone (2002) proposed the super-efficiency SBM model to further perform the efficiency measurement of the SBM effective decision units and realize the complete ranking of decision units, producing more objective and accurate efficiency measurement results. Therefore, based on MaxDEA8.3 software, this study uses the super-SBM DEA model containing undesired outputs to measure the eco-efficiency of tourism in the Beijing-Tianjin-Hebei region, so as to fully solve the problem that multiple decision-making units may be effective at the same time. The super-efficient SBM-DEA model is constructed as follows:

$$\rho^* = \min \frac{1 + \frac{1}{m}\sum_{i=1}^{m} \frac{s_i^-}{x_{ik}}}{1 - \frac{1}{q1+q2}\left[\sum_{r=1}^{q1} \frac{s_r^+}{y_{rk}} + \sum_{t=1}^{q2} \frac{s_t^{b-}}{b_{tk}}\right]}$$

$$\begin{aligned} \text{s.t.} & \sum_{j=1, j\neq k}^{n} x_{ij}\lambda_j - s_i^- \le x_{ik} \\ & \sum_{j=1, j\neq k}^{n} y_{rj}\lambda_j + s_r^+ \ge y_{rk} \\ & \sum_{j=1, j\neq k}^{n} b_{tj}\lambda_j - s_i^{b-} \le b_{tk} \\ & \lambda, s^-, s^+, s^{b-} \ge 0 \\ & \mathrm{i} = 1, 2, \ldots, \mathrm{m}; \mathrm{r} = 1, 2, \ldots\ldots, \mathrm{q}_1; \mathrm{t} = 1, 2, \ldots., \mathrm{q}_2; \\ & \mathrm{j} = 1, 2, \ldots, \mathrm{n}\,(\mathrm{j} \neq \mathrm{k}) \end{aligned} \quad (1)$$

In this expression, ρ^* indicates the eco-efficiency value; n, m, q_1, and q_2 denote the number of DMUs, inputs, desirable outputs, and undesired outputs, respectively; s_i^-, s_r^+, and s_t^{b-} represent the input slack, desirable output slack, and undesired output slack, respectively.

The eco-efficiency of DMU is considered to be in an effective state only when $\rho^*\ge 1$, and the eco-efficiency of input–output elements is considered ineffective when $\rho^*<1$.

3.1.2 Kernel density function

The kernel density function estimation method is an important tool to study the non-equilibrium of spatial distribution by estimating the probability density of variables, describing the distribution posture of variables with density curves, and reflecting the information on distribution location, shape, and extension of variables (Chen et al., 2019). Moreover, the kernel density function is weakly dependent on the model and has strong robustness. If the kernel density function exhibits two-wave distribution postures, it indicates that there is convergence in two directions in the economy, and if the height of the wave exhibits a decreasing trend, it indicates that the differences in the values of the evaluated economic attributes keep decreasing, and the concentration of the distribution also exhibits a decreasing trend. In the data, X_1, X_2, ..., X_n, that is, the probability density of the random variable at point X, is estimated using the following formula (Hou and Yao, 2018):

$$f(X) = \frac{1}{nh}\sum_{i=1}^{n} K\left(\frac{X_i - \bar{X}}{h}\right) \tag{2}$$

where n represents the number of observations, which in this study refers to 13 cities in the Beijing-Tianjin-Hebei region; X_i denotes the observed value; X^{-} stands for the mean value; h represents the density estimation bandwidth, and $K(u)$ denotes the kernel function.

3.1.3 Spatial correlation analysis

3.1.3.1 Global spatial auto-correlation

The global spatial auto-correlation portrays the clustering of the spatial distribution of tourism eco-efficiency in the regional space as a whole and examines whether there are spatial clustering characteristics. Moran's index is used to analyze the global spatial correlation of tourism eco-efficiency in the Beijing-Tianjin-Hebei region, and the Moran's index is calculated as follows:

$$\text{Moran's I} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(x_i - \bar{x})(x_j - \bar{x})}{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(x_i - \bar{x})^2} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(x_i - \bar{x})(x_j - \bar{x})}{S^2\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}} \tag{3}$$

$$S^2 = \frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2$$

In the equations, n represents the total number of cities; w_{ij} represents the spatial weight matrix; $i = 1, 2,...,n$, $j = 1, 2,...,n$; x_i and x_j stand for the tourism eco-efficiency of cities i and j, respectively; x^{-} represents the mean value of tourism eco-efficiency, and S^2 indicates the variance of tourism eco-efficiency.

3.1.3.2 Local spatial auto-correlation

Local spatial auto-correlation is used to measure the local correlation between a certain region and the neighboring regions. It is applied to test the agglomeration and dispersion effects between regions. Usually, Moran scatter plots are used to analyze spatial correlation. Local Moran's I can be calculated as follows:

$$I_i = \frac{n(x_i - x)\sum_{j=1}^{n} w_{ij}(x_i - x)}{\sum_{i=1}^{n}(x_i - x)^2} \tag{4}$$

In Eq. 3, I_i denotes the local Moran's index of city i; w_{ij} represents the spatial weight matrix and the proximity or distance between regional units i and j, which is equivalent to the correlation coefficient. If the local Moran's index is positive, it indicates the agglomeration distribution of attributes with similar types, that is, a high-value area is surrounded by a high-value area, or a low-value area is surrounded by a low-value area. In contrast, if it is negative, it means aggregation distribution of heterogeneous attribute values, that is, a high-value area is surrounded by a low-value area, or a low-value area is surrounded by a high-value area. The larger the absolute value of I_i, the higher the degree of aggregation.

3.1.4 Panel tobit regression analysis

The panel Tobit regression model was proposed by American economist Tobin (1958) to mainly solve the problem of limited or truncated dependent variables. In this study, the value of tourism eco-efficiency in the Beijing-Tianjin-Hebei region is greater than 0, which is a censored data. If ordinary least square method (OLS) is used, it will produce deviation, resulting in inconsistency with the actual results. Therefore, this study uses the panel Tobit regression model to analyze the influencing factors of tourism eco-efficiency in the Beijing-Tianjin-Hebei region, to avoid the problem of inconsistent and biased estimation of parameters. The expression of the model is as follows:

$$Y = \begin{cases} Y_i = \beta_0 + \beta_t{}^{*}X_i + \varepsilon_i. & Y^{*} > 0, \\ 0 & Y^{*} \le 0 \end{cases} \tag{5}$$

where Y denotes the restricted dependent variable vector; X stands for the explanatory variable; β_0 represents the constant term; β_t represents the estimated coefficient of the model; $t = 1, 2, 3. . . . . .n$, with n representing different years; ε_i represents the random error disturbance term, ε_i ~ N (0, σ2).

3.2 Construction of indicators

Referring to the results of previous research (Liu. et al., 2021; Wang et al., 2021; Zha et al., 2020), this study selects the number of A-level scenic spots, the number of practitioners in the tertiary industry, and the investment in fixed assets of tourism to represent the input indicators. The total tourism revenue is used to represent the expected output, whereas the tourism sewage discharge, tourism domestic garbage discharge, and tourism SO_2 emissions represent undesired output indicators.

3.3 Data sources

The data of this study are mainly from the China Urban Statistical Yearbook, China Urban Construction Statistical Yearbook, Beijing Statistical Yearbook, Tianjin Statistical Yearbook, Hebei Economic Yearbook, Hebei Municipal

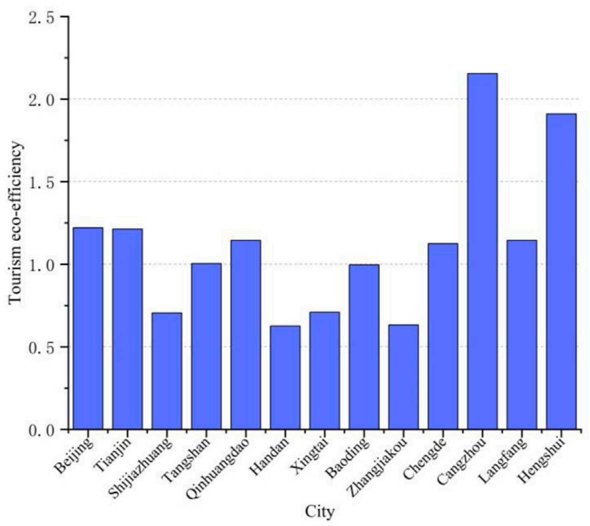

FIGURE 1
The average value of tourism eco-efficiency in the Beijing-Tianjin-Hebei region from 2010 to 2019.

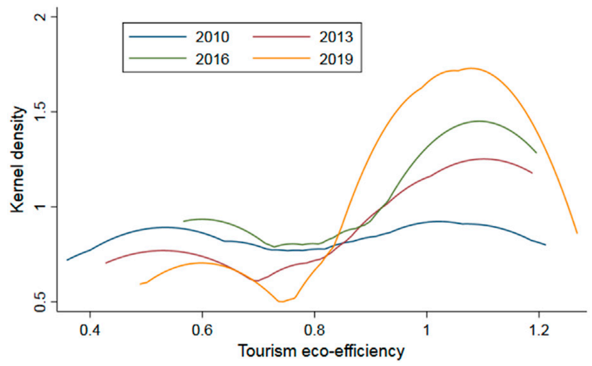

FIGURE 2
Kernel density analysis of tourism eco-efficiency.

Statistical Yearbooks, and the statistical bulletins on the national economic and social development of each city in the corresponding years. For some of the missing data, this study uses the linear interpolation method to complete them.

4 Results

4.1 Regional characteristics of tourism eco-efficiency

According to the results, the average value of tourism eco-efficiency in the Beijing-Tianjin-Hebei region from 2010 to 2019 is 0.846, which reveals an overall trend of small fluctuation and increase from 0.803 to 0.940. Figure 1 depicts the tourism eco-efficiency of each city in the Beijing-Tianjin-Hebei region from 2010 to 2019. We find that cities with higher tourism eco-efficiency are Beijing, Tianjin, and Langfang, which are closely connected geographically, whereas cities with lower tourism eco-efficiency are Hengshui, Zhangjiakou, and Shijiazhuang. From the perspective of geographical location, the farther the distance from the two central cities of Beijing and Tianjin, the lower the tourism eco-efficiency.

Overall, there is a large gap in tourism eco-efficiency in the region, with cities around Beijing and Tianjin having a relatively high tourism eco-efficiency, because of rich tourism resources and good tourism industrial development foundation. In these cities, there is little long-term negative impact on the environment, thus the efficiency value is at a high level. However, other cities which didn't take into account the resource limitation, ecological damage and other issues at early stage, may have lower tourism eco-efficiency value, which restricts the sustainable development of the regional tourism industry.

4.2 Spatial-temporal distribution characteristics of tourism eco-efficiency

As depicted in Figure 2, the overall trend reveals that the tourism eco-efficiency of 2010, 2013, 2016, and 2019 indicates a "bimodal" distribution trend, implying that the two levels of tourism eco-efficiency are more obvious. The tourism eco-efficiency of the first wave is in the range of 0.4–0.6, and that of the second wave is in the range of 1–1.2. In general, the number of cities in the first wave is the same as that in the second wave. From the state of the kernel density function distribution curve, the wave crests of the tourism eco-efficiency kernel density curves of the 4 years move to the right and become higher in height and narrower in width, indicating that, in general, the tourism eco-efficiency of the Beijing-Tianjin-Hebei region exhibits an upward trend, but the differences between the high and low values are still obvious, and the two-level differentiation still exists.

For a more comprehensive analysis of the dynamic evolution of tourism eco-efficiency in the Beijing-Tianjin-Hebei region from 2010 to 2019, the natural breaks method (Jenks) in ArcGIS is used to classify the mean tourism eco-efficiency values (TE) of 13 cities in the Beijing-Tianjin-Hebei region. We classify the regions into five types—high-efficiency areas ($1.14 \leq TE \leq 1.27$), relatively high-efficiency regions ($1.05 \leq TE \leq 1.33$), medium-efficiency areas ($0.79 \leq TE \leq 1.04$), low-efficiency areas ($0.58 \leq TE \leq 0.78$), and inefficiency areas ($0.36 \leq TE \leq 0.57$). In this study, the spatial distribution maps of tourism eco-efficiency in the Beijing-Tianjin-Hebei region in 2010, 2013, 2016, and 2019 are selected to

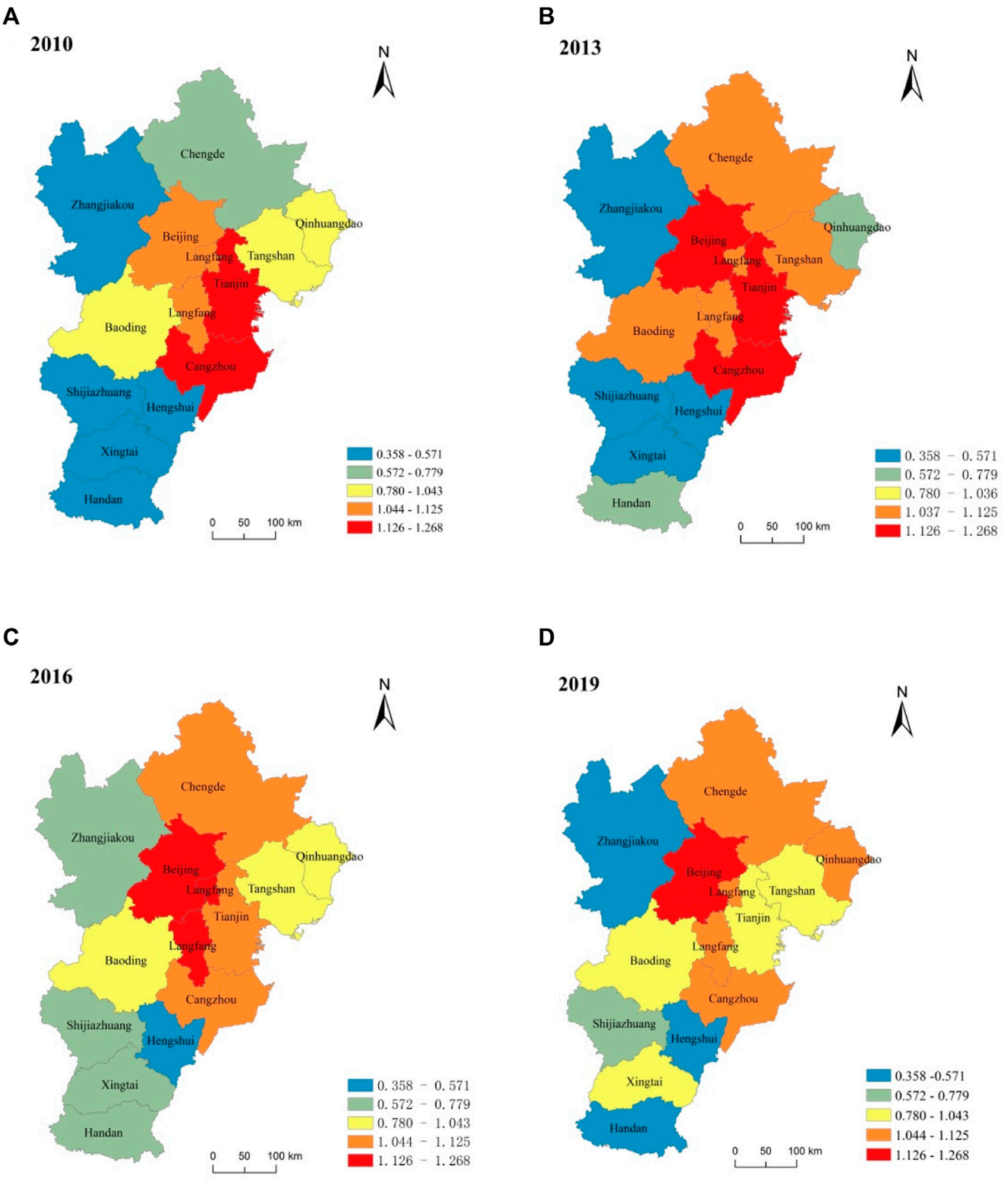

FIGURE 3
Spatial distribution of tourism eco-efficiency in the Beijing-Tianjin-Hebei region.

demonstrate the dynamic evolution of tourism eco-efficiency (Figure 3).

In 2010, Tianjin and Cangzhou were the areas with the highest efficiency; Beijing and Langfang belonged to the relatively high-efficiency areas, and Qinhuangdao and Baoding belonged to the medium efficiency areas, but their tourism eco-efficiency values were above 1. The high- and relatively high-efficiency regions were mainly in the central cities of Beijing and Tianjin and their surrounding areas. From 2013 to 2016, the number of inefficient cities decreased significantly, whereas areas with low and medium efficiency increased significantly. The tourism eco-efficiency of Tianjin and Cangzhou decreased from a relatively high to medium-efficiency area, whereas the tourism eco-efficiency of Chengde, Shijiazhuang, Xingtai,

TABLE 1 Global Moran's index of tourism eco-efficiency in the Beijing-Tianjin-Hebei region.

Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Moran's I	0.4198	0.4494	0.3066	0.2773	0.348	0.4855	0.4671	0.4293	0.3998	−0.0649
Z(I)	2.5884	2.7234	1.9783	1.8375	2.2196	2.905	2.81	2.6194	2.5186	0.04298
P	0.007	0.007	0.037	0.043	0.018	0.004	0.00271	0.007	0.01	0.0982

Chengde, and other cities improved substantially. In 2019, there were five cities in the high- and relatively high-efficiency areas, with an increase of one city compared to that in 2016. Beijing remained in the high-efficiency region and is the representative of green tourism development in the Beijing-Tianjin-Hebei region; the number of cities in medium-efficiency areas increased, but the tourism eco-efficiency of Zhangjiakou and Handan dropped to inefficiency again.

In summary, the analysis reveals that there was a small increase in the high and relatively high tourism eco-efficiency areas in the Beijing-Tianjin-Hebei region from 2010 to 2019. The number of cities in the inefficiency areas experienced an evolutionary trend of first decreasing and then increasing. Its distribution range narrowed from five cities—Zhangjiakou, Shijiazhuang, Hengshui, Xingtai, and Handan—in 2010 to four cities—Zhangjiakou, Shijiazhuang, Hengshui, and Xingtai—in 2013, and decreased to only one city—Hengshui—in 2016. In 2019, Zhangjiakou and Handan returned to the inefficiency level again. Hengshui was always at the inefficiency level during the study period.

4.3 Spatial differences in tourism eco-efficiency

4.3.1 Global spatial autocorrelation analysis

To explore the spatial autocorrelation characteristics of tourism eco-efficiency in the Beijing-Tianjin-Hebei region from 2010 to 2019, we use Geoda1.10 software to calculate the Moran's index of tourism eco-efficiency in the Beijing-Tianjin-Hebei region for each year, as presented in Table 1. According to the calculated p and z values, only the results in 2019 are not statistically significant. The results of other years passed the significance test, at least at the 5% level, indicating that the tourism eco-efficiency in the Beijing-Tianjin-Hebei region exhibited significant positive spatial autocorrelation characteristics from 2010 to 2018. In 2019, the Moran's index of tourism eco-efficiency in the Beijing-Tianjin-Hebei region changed to a negative value, indicating that the spatial agglomeration feature of tourism eco-efficiency weakened; the spatial spillover effect of high-efficiency cities was not significant, and the spatial divergence feature of tourism eco-efficiency between neighboring cities strengthened. Although tourism eco-efficiency in 2019 was spatially irrelevant, the overall tourism eco-efficiency in the Beijing-Tianjin-Hebei region had obvious clustering characteristics, which is conducive to the coordinated development of the tourism economy in the region.

4.3.2 Local spatial autocorrelation analysis

The spatial evolution of tourism eco-efficiency among cities in the Beijing-Tianjin-Hebei region is depicted on the Moran scatterplot of tourism eco-efficiency for 2010, 2013, 2016, and 2019 (Figure 4). The Moran scatter plot is divided into four quadrants, and different quadrants indicate the local spatial correlation patterns between the tourism eco-efficiency of different cities and the tourism eco-efficiency of their surrounding cities (Zou et al., 2015). Quadrant I (H-H) indicates that cities with high tourism eco-efficiency are surrounded by cities with high tourism eco-efficiency, i.e., a high–high spatial correlation pattern, and cities in this quadrant positively influence the tourism eco-efficiency of surrounding cities. Quadrant II (L-H) indicates that cities with low tourism eco-efficiency values are surrounded by cities with high tourism eco-efficiency values, i.e., low–high spatial correlation pattern, and cities located in this quadrant are surrounded by cities with high and low tourism eco-efficiency, and such areas have large spatial differences and negative spatial autocorrelation of tourism eco-efficiency. Quadrant III (L-L) indicates that cities with low tourism eco-efficiency values are surrounded by cities with low tourism eco-efficiency values, i.e., low–low spatial correlation pattern, and cities in this quadrant have a negative influence on the tourism eco-efficiency of surrounding cities. Such areas have small spatial differences and are dependent on each other. Quadrant IV (H-L) indicates that cities with high tourism eco-efficiency values are surrounded by cities with low tourism eco-efficiency values, i.e., high–low association pattern, and such areas have large spatial differences with the surrounding areas.

Drawing on spatial-temporal leapfrogging method proposed by Rey, (2010), we measure the changes in the spatial association patterns of tourism eco-efficiency in different periods. There are four types of leap paths: in the first one, the observed area leaps to the neighbor quadrant; in the second one, the observed area leaps to the interphase quadrant; in the third one, the observed area does not leap but has a negative correlation with the surrounding area; in the fourth one, the observed area does not leap and has a positive correlation with the surrounding area.

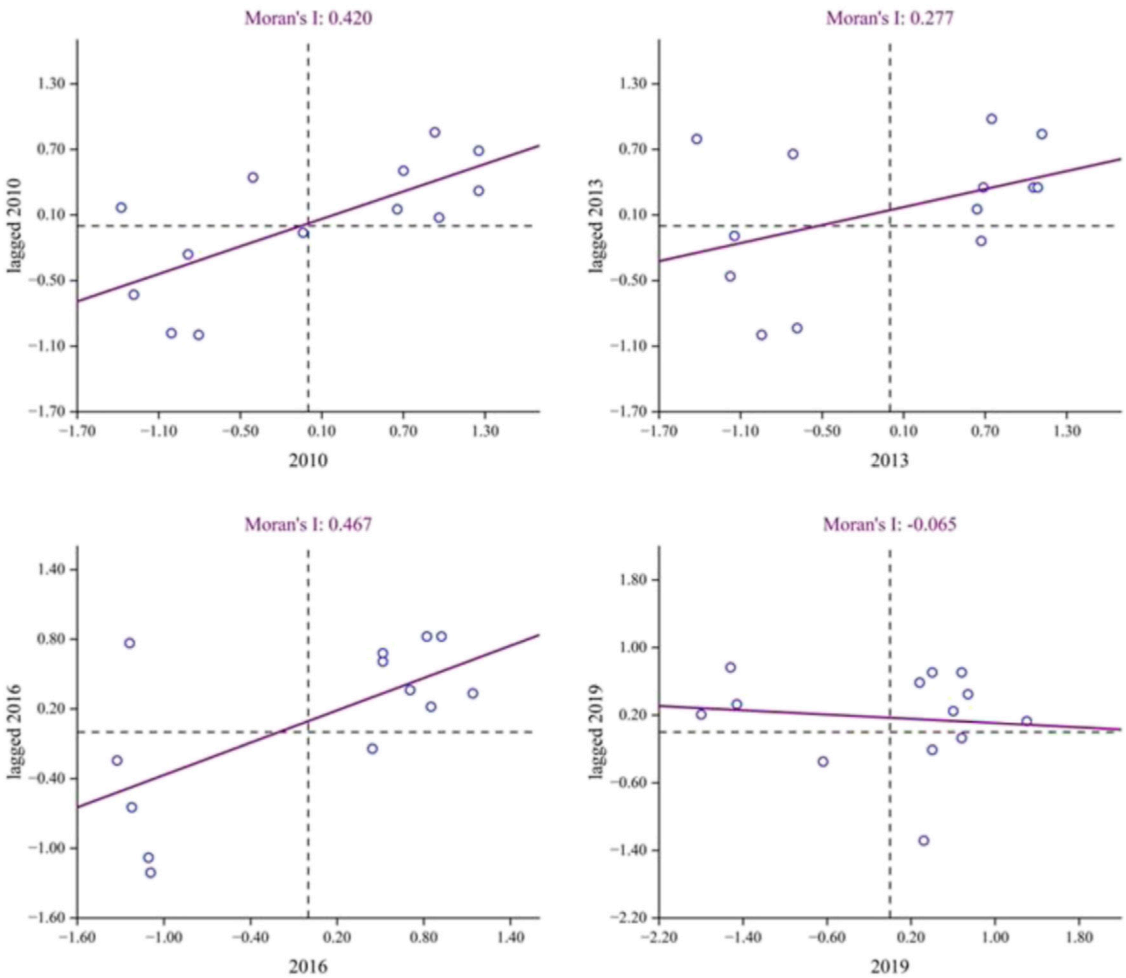

FIGURE 4
Moran scatter plot of tourism eco-efficiency.

TABLE 2 The spatial distribution of tourism eco-efficiency in the Beijing-Tianjin-Hebei region.

	Quadrant I (high–high)	Quadrant II (low–high)	Quadrant III (low–low)	Quadrant IV (high–low)
2010	Beijing, Langfang, Tianjin, Cangzhou, Tangshan, and Qinhuangdao	Zhangjiakou and Chengde	Baoding, Shijiazhuang, Hengshui, Xingtai, and Handan	
2013	Beijing, Langfang, Tianjin, Cangzhou, Tangshan, and Chengde	Zhangjiakou and Qinhuangdao	Shijiazhuang, Hengshui, Xingtai, and Handan	Baoding
2016	Beijing, Langfang, Tianjin, Cangzhou, Tangshan, Qinhuangdao, and Chengde	Zhangjiakou	Shijiazhuang, Hengshui, Xingtai, and Handan	Baoding
2019	Beijing, Langfang, Tianjin, Tangshan, Qinhuangdao, and Chengde	Zhangjiakou, Hengshui, and Handan	Shijiazhuang	Baoding, Cangzhou, and Xingtai

Notes: It was sorted out according to Moran scatter diagram by Geoda1.10 software.

The position of each city in the Moran scatter plot for each year is presented in Table 2. The research results reveal that: 1) There is a significant spatial dependence of tourism eco-efficiency in the Beijing-Tianjin-Hebei region, i.e., the tourism eco-efficiency level and the neighboring regions have clustering characteristics. The main manifestation is that the cities around

TABLE 3 Variable descriptions of the influencing factors.

Variable	Symbol	Definition	Unit
Economic development	ED	Per capita GDP	Yuan
Industrial structure	IS	Percentage of the tertiary industry in GDP	%
Urbanization	UR	Population of the city	%
Technological progress	TEC	Number of patents granted	Item
Environmental regulation	ER	Environmental Regulation Intensity Index	—
Traffic Conditions	RD	Road network density	km/hundred square kilometers

Beijing and Tianjin are clustered in the diffusion effect area of "high–high" clustering, whereas the rest are mostly clustered in the low growth area of "low–low" clustering, indicating a significant positive correlation. 2) Seven cities experienced leapfrog changes, and all of them belong to the first type, i.e., the observed area leaps to the near quadrant; the area that does not leapfrog is mainly concentrated in the high growth area (high–high), which has a positive correlation with the surrounding area. 3) Before 2019, cities in the Beijing-Tianjin-Hebei region were mainly distributed in Quadrants I and III, whereas in 2019, the spatial distribution pattern of tourism eco-efficiency changed significantly, with more cities falling into Quadrants II and IV. This reveals that the tourism eco-efficiency in the Beijing-Tianjin-Hebei region gradually changed from an initial positive spatial correlation to a spatial competition, indicating that the spatial competition relationship between cities gradually became greater than the spatial cooperation relationship, and the spatial differentiation of tourism eco-efficiency among cities gradually strengthened.

4.4 Factors influencing the spatial and temporal evolution of tourism eco-efficiency

4.4.1 Influencing factors

The differences in the temporal and spatial evolution of tourism eco-efficiency are influenced by a number of factors. Based on the existing research literature, the relevant indicators of influencing factors of tourism eco-efficiency are selected as shown in Table 3. 1) Economic development level (ED). Tourism development is closely related to the level of regional economic development. High level of regional economy can provide more convenient conditions for tourism, also introduce environmental pollution. The per capita GDP is selected to measure the economic development level. 2) Industrial structure (IS). As an important part of the tertiary industry, the supporting services of tourism benefit from other corresponding industries, thus, the upgrading and rationalization of industrial structure have an important impact on tourism eco-efficiency. The percentage of the value of the tertiary industry in GDP is selected to represent the industrial structure. 3) Urbanization level (UR). The improvement of urbanization level effectively promotes the development of tourism, provides resources such as capital, talents, technology and information for the improvement of tourism ecological environment, and plays a positive role in promoting energy conservation and emission reduction. On the other hand, from the perspective of economic theory, urbanization may lead to aggravated environmental pollution because of requirement increasing for urban infrastructure and ecological environmental resources. Urbanization is represented by the population of the city. 4) Technological progress (TEC). Technological progress can reduce the energy consumption of tourism, reduce the production of waste water and garbage, and improve the ecological efficiency of tourism. We select the number of patents granted to characterize the technological progress. 5) Environmental Regulation (ER). Environmental regulation is a restraint mechanism for the coordination of tourism economic development and ecological environment protection. From the perspective of pollution control effect, we select three indicators of solid waste comprehensive utilization, sewage treatment and living garbage disposal rates to calculate environmental regulation intensity based on entropy weight method (Ren, et al., 2018; Wang and Wang, 2021). 6) Traffic conditions (RD). Traffic accessibility is the basic condition for tourism development. High accessibility to tourist destinations and convenient transportation in the region can save time cost of tourists, and improve tourism development level. Referencing to research by Li and Wang (2020), we choose road network density, that is, the ratio of highway mileage to regional area, to characterize regional traffic conditions.

Based on the panel data of the Beijing-Tianjin-Hebei region from 2010 to 2019, this study constructs a panel regression model as follows:

$$EE_{it} = \alpha_0 + \beta_1 ED_{it} + \beta_2 IS_{it} + \beta_3 UR_{it} + \beta_4 TEC_{it} + \beta_5 ER_{it} + \beta_6 RD_{it} + \varepsilon_{it} \quad (6)$$

where EE_{it} represents the tourism eco-efficiency of city i in year t; α_0 is a constant term; β_i (i = 1,2, ..., 5) represents the undetermined coefficient of each variable, and ε_{it} stands for a random interference item.

TABLE 4 Tobit regression results.

Variable	Coefficient	Standard error	Z-Statistics	*p*-value
pgdp	−3.77e-06***	1.15e-06	−3.27	0.001
Is	−0.0096***	0.0032115	−3.00	0.003
Ur	1.7432***	0.4567944	3.82	0.000
Tec	4.23e-06***	1.36e-06	3.10	0.002
Er	−0.0183	0.0995529	−0.18	0.854
Rd	0.0005	0.0009497	0.52	0.600

Note: *** denotes significance at the 1% level.

4.4.2 Analysis of the tobit regression results

The regression results are presented in Table 4.

First, economic development and tourism eco-efficiency are negatively correlated at the 1% significance level. This indicates that the green development level of tourism in the Beijing-Tianjin-Hebei region is low, and high emissions and energy consumption are still the main problems in tourism development. Moreover, this reveals that the development of the economy in the Beijing-Tianjin-Hebei region is still on the left side of the inverted U-curve of the Environmental Kuznets Curve. Despite the growth in GDP, environmental management is still facing serious challenges. Therefore, it is urgent to explore green tourism development.

Second, the correlation between the industrial structure and the tourism eco-efficiency is significantly negative. This indicates that industrial upgrading inhibits the development of tourism eco-efficiency. This may be because Hebei Province is dominated by traditional industries, and the development of modern service industries is relatively slow, so the upgrading of industrial structure will not improve eco-efficiency in the short term. However, as the coefficient is relatively small, its negative impact is not significant.

Third, the level of urbanization exerts a significant and positive impact on tourism eco-efficiency. The current continuous acceleration of the urbanization process in the Beijing-Tianjin-Hebei region is conducive to the agglomeration effect of the tourism industry, thus promoting technological progress and scale efficiency. The mutually reinforcing relationship between urbanization rates and tourism development is recognized by most scholars, with the studies of Wang et al. (2016) and Xu et al. (2018) concluding that the level of urbanization is positively and significantly correlated with tourism efficiency when studying the factors influencing tourism efficiency and performance in different regions. This indicates that although urbanization put great pressure on the ecology and environment, resulting in increased pollution emissions, resource constraints, and damage to resources and the environment due to urban construction, it has a positive impact on tourism development, which outweighs its ecological nuisance. This results in a positive correlation coefficient between the level of urbanization and tourism eco-efficiency.

Fourth, technological progress has a significant influence on tourism eco-efficiency. However, the coefficient of influence is small, indicating that the positive contribution of the level of technological progress to tourism eco-efficiency in the Beijing-Tianjin-Hebei region is less obvious, which is consistent with the results in the study of Zeng (2020). Moreover, the results in the study of Jiao et al. (2018) also indicate that technological progress and innovation, represented by regional patent technology applications, can positively influence the total factor productivity of the tourism industry. On the one hand, technological progress can help tourism sites to innovate ecological and environmental protection activities, improve the efficiency of resource use, enhance the marginal output efficiency of factors, and improve tourism eco-efficiency. On the other hand, the intervention of modern technology has changed the traditional operation and management of tourism, while accelerating the renewal of tourism products and business models, but the R&D of patents has paid little attention to the technological innovation of the tourism economy. Moreover, technological innovations in the tourism economy have not been fully established with a green goal orientation and thus have had a limited effect on improving tourism eco-efficiency.

Fifth, the influence of environmental regulation on tourism eco-efficiency does not pass the significance test, indicating that the influence of environmental regulation on tourism eco-efficiency is not significant. On the one hand, when environmental regulation is strong, enterprises need to invest more capital and labor in environmental management, which may affect tourism economic output to a certain extent, thus inhibiting the improvement of tourism eco-efficiency. On the other hand, environmental regulation prompts tourism enterprises to pay attention to tourism energy consumption and pollution, promoting enterprise innovation, which has a positive effect on tourism eco-efficiency. The offsetting government effects make the impact of environmental regulation on tourism eco-efficiency insignificant. -Sixth, the impact of transportation conditions on tourism eco-efficiency does not pass the significance test, but the regression coefficient is positive, indicating that transportation accessibility contributes to tourism eco-efficiency to a certain extent. Meng et al. (2021) also found that a well-developed transportation network improves tourism development efficiency when studying tourism development efficiency in the Qinba Mountain region, whereas Gong et al. (2016) indicated that transportation conditions have a hindering effect on tourism industry efficiency, thus demonstrating that the influence of regional transportation conditions on tourism eco-efficiency is more complex.

5 Conclusions and recommendations

5.1 Conclusions

The essence of studying tourism eco-efficiency is to determine the impact of the ecological environment on tourism efficiency and comprehensively analyze the relationship between inputs and desired and non-desired outputs. This study estimates the tourism eco-efficiency of 13 cities in the Beijing-Tianjin-Hebei region from 2010 to 2019 using the super-efficiency SBM-DEA model and demonstrates three aspects of tourism eco-efficiency—characteristics, spatial analysis, and influencing factors. The main conclusions are as follows.

(1) During the study period, the mean value of tourism eco-efficiency in the Beijing-Tianjin-Hebei region is 0.846, which is relatively low. However, it shows a fluctuated increased trend, which is consistent with the existing research results on the eco-efficiency in the Beijing-Tianjin-Hebei (Li, B., et al., 2021). There are big differences among the cities, and the top three cities are Beijing, Tianjin, and Langfang. Because of weak economic foundation and relatively scared tourism resources of some cities in Hebei Province, the overall value of tourism eco-efficiency is not high. Supported by national policies, the advantages of late development are obvious, thus, there is still much room for improving the overall tourism eco-efficiency of the region.
(2) The tourism eco-efficiency of the region reveals an obvious polarization, but the gap among the cities tends to narrow, with a small increase in the high-efficiency areas of tourism. The number of low-efficiency areas experienced an evolutionary trend of first decreasing and then increasing. Hengshui always remained at a low level, with little change in its tourism eco-efficiency values. From 2010 to 2018, the tourism eco-efficiency in the Beijing-Tianjin-Hebei region exhibited a significant positive spatial autocorrelation characteristic, and the high-efficiency cities within the urban agglomeration experienced an obvious spatial spillover effect. In 2019, the spatial distribution pattern of tourism eco-efficiency changed significantly from an initial positive spatial correlation to a negative spatial correlation, indicating that the spatial differentiation of tourism ecological efficiency among cities strengthened.
(3) The tourism eco-efficiency of the Beijing-Tianjin-Hebei region is controlled by multiple factors, with the level of economic development and industrial structure having a negative impact on the tourism eco-efficiency of the region; the level of urbanization and technological progress can significantly promote the tourism eco-efficiency of the Beijing-Tianjin-Hebei region.

5.2 Recommendations

Based on the results of the empirical study, the following policy recommendations are put forward.

First, cities with high levels of tourism eco-efficiency have a pronounced spatially radiating and driving effect on cities at lower levels in the Beijing-Tianjin-Hebei region. Therefore, under the strategy of the Beijing-Tianjin-Hebei collaborative development, tourism resources and management technologies should be shared among different cities. Areas with high tourism eco-efficiency, such as Beijing and Tianjin, should play an important role in improving tourism eco-efficiency in neighboring cities. Moreover, Hebei Province needs to enhance its ability to absorb projects, technology, and other elements and actively respond to the radiation effect of Beijing and Tianjin.

Second, the regional industrial structure should be optimized and the upgrading efforts of industrial restructuring should be strengthened to improve tourism eco-efficiency. Optimizing the regional industrial structure requires strengthening the supply-side reform of the regional tourism industry to promote the coordination and adaptation of the tourism supply and demand structure. Moreover, as tourism is a comprehensive industry with many related industries, the Beijing-Tianjin-Hebei region needs to strengthen the relationship between tourism and other industries, improve the overall industry level, and extend the industrial chain.

Third, accelerating the urbanization process; further increasing capital investment to improve urban public infrastructure; advocating green production methods, green lifestyles, and green consumption patterns; and building eco-friendly cities will have a more significant impact on tourism development. The government should continue to innovate the management of environmental protection, clarify the property rights of environmental resources, give full play to the resource allocation role of markets, involve ecological and environmental resources as market factors in market allocation, and reduce energy consumption and pollution emissions.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

Conceptualization: YL and YZ; methodology: YL; formal analysis: YL and YZ; investigation: YZ; writing—original draft preparation: YZ; writing—review and editing, YL. All authors have read and agreed to the published version of the manuscript.

Funding

This paper was supported by National Social Science Foundation of China [grant number: 21FJYB023], Natural Science Foundation of Beijing, China [grant number: 9192002], and Social Science Foundation of Beijing,China [grant number: 19YJA002].

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 25 November 2022
DOI 10.3389/fenvs.2022.1043325

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OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Environmental Economics and Management,
a section of the journal
Frontiers in Environmental Science

RECEIVED 13 September 2022
ACCEPTED 24 October 2022
PUBLISHED 25 November 2022

CITATION
Xia M, Cai HH and Yuan Q (2022), Can board climate-responsible orientation improve corporate carbon performance? The moderating role of board carbon awareness and firm reputation.
Front. Environ. Sci. 10:1043325.
doi: 10.3389/fenvs.2022.1043325

Can board climate-responsible orientation improve corporate carbon performance? The moderating role of board carbon awareness and firm reputation

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Overwhelming evidence from prior research suggests the functions of the board of directors have a vital influence on carbon performance. However, very little is known about the moderating effect of board functions. This study attempts to fill this gap by developing and empirically testing a conceptual model that highlights the role of board carbon awareness and firm reputation in the relationship between board climate-responsible orientation (BCO) and carbon performance. Using a fixed effect model to analyze data from 665 US listed firms covering a period of 2010–2019, we find that BCO and carbon performance show a U-shaped non-linear relationship. Increased experience of BCO improves corporate carbon performance. The results also provide evidence of the moderating effect of carbon awareness and firm reputation on the relationship between BCO and carbon performance. Carbon awareness reduces symbolic emission reduction actions in carbon management, while, firm reputation will cause symbolic emission reduction actions. Besides, splitting the sample according to firm size and carbon dependency shows BCO has a better effect on the carbon performance of small or medium-sized and high carbon-dependency firms. The findings have important implications for managers to use firm governance mechanisms to improve carbon performance.

KEYWORDS

board climate-responsible orientation, carbon awareness, firm reputation, carbon performance, agency theory, resource dependence theory, legitimacy theory

1 Introduction

Greenhouse gases (GHG) produced by firms' activities have become a serious problem for corporate environmental accountability. More and more firms are aware of the increased costs and risks associated with climate change (World Economic Forum, 2020). Carbon performance defined as firm actual or outcome-oriented GHG emissions is an indicator to measure corporate governance effectiveness in carbon emission reduction (Bui et al., 2020; Nuber and Velte, 2021). Firms are both emitters, and solvers of carbon emissions (Klettner

 10.3389/fenvs.2022.1043325

TABLE 1 Variable definition and measurement.

Variable name	Definition	Sign	Theoretical justification	Data source
Dependent variables				
Carbon emissions per revenue performance (*RCP*)	The natural logarithm of the inverse of scope 1 and 2 carbon emissions/ total operating revenue			CDP
Carbon emissions per full time equivalent employee performance (*ECP*)	The natural logarithm of the inverse of scope 1 and 2 carbon emissions/ equivalent employees			CDP
Independent variables				
Board climate-responsible orientation (*BCO*)	The number of years that the board occupied the highest level of direct responsibility for climate change within the organisation	+	Agency theory	CDP
Board climate-responsible orientation quadratic (BCO^2)	The square of BCO	−	Agency theory	CDP
Moderators				
Board carbon risk awareness (*Risk*)	Dummy variable with the value of one if current and/or anticipated regulatory requirements related to climate change present significant risks for your company	+/−	Resource dependence theory	CDP
Board carbon monitoring awareness (*Boardexm*)	Dummy variable with the value of one if have board-level monitoring of climate-related issues	+/−	Resource dependence theory	CDP
Firm reputation (*Gdwl*)	Firm annual goodwill	−	Legitimacy theory	Compustat
Control variables				
Firm emission trading schemes (*Scheme*)	Dummy variable with the value of one if corporations participate in any emission trading schemes			CDP
Firm managing climate change incentives (*Incentive*)	Dummy variable with the value of one if corporations provide incentives for managing climate change issues, including attaining targets			CDP
Board size (*Bsize*)	The natural log of the number of directors serving on the board			Compustat
Executive directors (*Exdirector*)	The natural log of total number of executive directors			Compustat
Firm size (*Size*)	The natural logarithm of the number of employees at the end of the fiscal year			Compustat
Capital intensity (*Asset*)	The natural logarithm of the ratio of property, plant and equipment to total assets			Compustat
Return on asset (*Roa*)	The natural logarithm of profit after tax, divided by total assets			Compustat
Capital expenditures (*Capex*)	The natural logarithm of the total capital divided by total sales			Compustat
Slack resources (*Slack*)	The natural logarithm of current assets divided by current liabilities			Compustat
Market-to-book ratio (*Mtbt*)	The natural logarithm of the ratio of market-to-book value of equity			Compustat

Notes: Carbon Disclosure Project (CDP) is a United Kingdom-based not-for-profit charity organization that collects and disseminates greenhouse gas-related information voluntarily disclosed by firms. Compustat is the historical data of detailed quarterly and annual financial statements and financial indicators of listed corporations in the United States and Canada.

et al., 2014). In response to the prominent climate change problem, firms have begun to consider environmental responsibilities, establishing mitigation strategies and conducting carbon disclosure (Gallego-Álvarez et al., 2015).

Corporate carbon performance has gained substantial attention due to firms facing increasing and multiple social, economic, and regulatory pressures (Moussa et al., 2020). Corporate governance effectiveness plays a critical role in addressing corporate environmental and climate-related risks, and monitoring a firm's engagement in carbon initiatives (Peters and Romi, 2014). Researchers try to identify and improve these corporate governance mechanisms to successfully improve carbon performance. The board as an effective means of corporate governance, influences firm decision-making through its monitoring functions. In January 2019, the World Economic Forum published a white paper titled 'How to Set Up Effective Climate Governance on Corporate Boards: Guiding Principles and Questions'. The board needs to take primary responsibility for corporate climate governance and provide guidance for climate governance. More and more scholars are trying to establish a theoretical framework or understanding relationship between the board characteristics and corporate environmental performance (Dixon-Fowler et al., 2017; Hussain et al., 2018; Homroy and Slechten, 2019; Shahbaz et al., 2020; Aguilera et al., 2021; Orazalin and Mahmood, 2021). The role of boards in reducing carbon emissions and environmental orientation have become a new focal point of board characteristics (Luo and Tang, 2021; Kyaw et al., 2022). Different scholars have proposed the positive and negative effects of this characteristic on carbon performance (Prado-Lorenzo and Garcia-Sanchez, 2010; De Villiers et al., 2011; Haque, 2017). This study will more clearly classify the impact of BCO on corporate carbon performance, and the mechanisms that cause these effects.

Monitoring management and accessible for information and resources are two functions of the board. To meet stakeholders' expectations of environmental responsibility, playing a good monitoring role in the corporate environmental practices have become an important objective for boards. Environmental practices require significant investments and have a long cycle of returns (Aragón-Correa and Sharma, 2003). Given this, management is often reluctant to pursue a high level of environmental performance and abandon immediate financial benefits. Management may be reluctant to incur expenses that do not have immediate financial benefits and therefore often focus on conservative initiatives that will maximize their reputation and financial benefits in the short term (Chen and Ma, 2021). Research based on agency theory suggests that the monitoring role of the board may not be significantly effective in this scenario because boards have no direct power over decision making. Some scholars find that firms pay attention to process-oriented environmental performance and carbon reduction plans (Moussa et al., 2020). In pursuit of reputational benefits, firms are more willing to take carbon reduction initiatives which can be easily communicated to the market and other stakeholders in order to change firm image immediately. However, the actual carbon performance has not improved in the form of reducing greenhouse gas emissions (Cho et al., 2012).

The effectiveness of the board depends not only on their monitoring orientation, but also on their influence on resource access (Erhardt et al., 2003; Konadu et al., 2022). Boards with a climate-responsible orientation tend to place greater emphasis on the monitoring of corporate environmental performance, ensuring that management better incur environmental responsibility (Russo and Harrison, 2005; Moussa et al., 2020). Based on resource dependence theory, a climate-responsible orientated board is more able to improve corporate environmental performance by accessing environment-related resources (Hillman and Dalziel, 2003). Directors' experience can enhance their ability to perform their board roles (Tejerina-Gaite and Fernández-Temprano, 2021). Long-tenured directors are able to assess the potential consequences of strategic decisions for short-term and long-term performance (Kor, 2006). The increased carbon-awareness of the board can be seen as a manifestation of the board's access to environment-related resources. The higher the awareness of carbon risk the better the ability to coordinate and deploy relevant resources (Luo and Tang, 2021). Board function is necessary not only to meet the environmental expectations of stakeholders but also to meet the social criteria of legitimacy. Firms must increase board effectiveness in carbon-related aspects to legitimize firm activities (Liao et al., 2015). Thus, we argue a relationship between board effectiveness and corporate environmental responsibilities actions: climate-responsible oriented boards produce symbolic emission reduction actions, but with the increase in access to environment-related resources, it will substantively affect corporate environmental responsibility actions to secure legitimacy. Our study raises the vital research question on whether board climate-responsible orientation improve corporate carbon performance and the role of board carbon awareness and firm reputation in the relationship between board climate-responsible orientation (BCO) and carbon performance.

This paper makes some contributions to the literature on corporate governance and carbon performance. We combine three theories, agency theory, resource dependence theory and legitimacy theory, to capture the complex relationship between BCO, board carbon awareness, firm reputation and carbon performance through an integrated analysis. This is conducted by using 665 firms from the United States, because the United States is in transition towards a low-carbon future and experiences negative growth in CO_2 emissions as GDP per capita continues to grow (Wang et al., 2018). Thus, the United States is a good example of how to study carbon emissions. Specifically, we contribute to the existing literature by first exploring the nonlinear relationships of BCO, identifying and explaining the symbolic and substantive relationships of BCO to the effectiveness of carbon performance. Second, we contribute to the literature by investigating how BCO influences carbon performance, and examining whether board carbon awareness and firm reputation moderate the relationship between BCO and carbon performance. When examining both direct relationships and moderating effects, we first attempt to capture both the symbolic and substantive effects of BCO on carbon performance through empirical models. Unlike past studies, the agency theory, resource dependence theory and legitimacy theory are combined to propose the impact of the board of directors on carbon performance should shift from the negative linear relationship of monitoring management function to the positive linear relationship of accessible for information and resources function. The turning point of this U-shaped relationship is generated by corporations to meet the legitimacy (Moussa et al., 2020). We integrate various theories and propose a new conceptual framework to make the impact process of the board of directors on carbon performance more complete and have theoretical support.

The rest of this paper is organized as follows. Section 2 presents the theoretical background and develops our hypotheses. Section 3 presents current status of climate change and carbon emissions reforms in the united states. Section 4 presents research design. Section 5 presents the results of the empirical research. Section 6 presents the results of moderating effect. Section 7 presents the discussion.

2 Theoretical background and hypotheses development

Firms are facing climate change issues that are becoming increasingly prominent and they are expected to be accountable not only for their financial performance but also for their social impact. As an effective means of internal governance, the board of directors plays a critical role in addressing firms' environmental and climate-related risks and monitoring a firm's engagement in carbon initiatives (Peters and Romi, 2014). Carbon performance is a unique dimension of environmental performance, which is regulated by specific legislation and regulations. The internal governance mechanism must meet legality requirements (He et al., 2021). The board achieves effective governance of corporate carbon performance through enhancing the two functions of monitoring and resource provision (Hillman and Dalziel, 2003; De Villiers et al., 2011). The role of board governance effectiveness on carbon performance is viewed from different theoretical perspectives, depending on agency, resource dependency, and legitimacy theories. The main thesis of each of these theories is discussed below, leading to hypothesis development.

Legitimacy theory proposes the concept of social contract, whereby organizations must satisfy certain social regulations that exist in society. Thus, firm activities must meet societal expectations to establish and improve legitimacy. These social expectations change over time, and require firms to be constantly responsive to their operation environment (Deegan, 2002). With increasing climate change pressures on firms, they must showcase good carbon performance to gain and maintain legitimacy (Bansal and Clelland, 2004). Firms with high legitimacy threats are more likely to take actions to demonstrate concern for climate change, because of better resources, and less scrutiny (Meyer and Rowan, 1977; Salancik and Pfeffer, 1978; Alsaifi et al., 2020).

The agency theory is the theoretical underpinning for the board's monitoring function. The theory assumes a conflict of interest between managers with control and shareholders with ownership. Managers incur agency costs when they pursue self-interest at the expense of profit maximization (Hoskisson et al., 2009). The board can reduce agency costs by monitoring the behavior of agents (managers) (Daily et al., 2003). In the context of climate change, agency theory is more oriented towards the conflict between financially oriented shareholders and environmentally oriented stakeholders. Managers tend to over-invest in environmental performance to gain reputation (Malmendier and Tate, 2005). This over-investment is a waste of resources that can damage firm value (Ferrell et al., 2016). Board monitoring is a means of effective internal control, and its vigilance has a strong influence on firms' strategic choices (Chari et al., 2019). Some scholars argue that the ability of the board to effectively monitor environmental policy is contextually dependent (Tuggle et al., 2010). When board members have an economic incentive to monitor environmental performance, they will be more vigilant in exercising their responsibility for monitoring.

Resource dependence theory focuses on the board's ability to access resources. The board of directors generates human capital and relational capital through four types of resource provisioning advice and counsel, legitimacy, broadening information channels with outsiders, and prioritizing access to external resources (Kor and Sundaramurthy, 2009). Different directors can provide different types of resources to the board. The resources and expertise accumulated by directors from external experience, including environmental aspects, can guide the board's strategic decisions (Kor and Misangyi, 2008). Some scholars argue that resource-rich directors are positively associated with good environmental performance because they are more likely to be knowledgeable about environmental issues and more suited to a resource provision role in the pursuit of corporate positive environmental performance (de Villiers et al., 2011).

When explaining the influence of BCO on carbon performance, we implement multiple theoretical frameworks, including combining agency theory, resource dependence theory and legitimacy theory to develop the hypotheses.

2.1 Board climate-responsible orientation and carbon performance

Environmental protection and related strategies are increasingly important for corporate development. Good environmental performance promotes corporations to achieve the best gains (Barnett and Salomon, 2006). The effectiveness of board monitoring gradually leads to improving corporate environmental performance and carbon performance to ensure that managers better pursue environmental performance and assume environmental responsibility (Russo and Harrison, 2005; Hafsi and Turgut, 2013). Boards with a climate-responsible orientation are more likely to exert monitoring pressure on managers to ensure corporate responsibility for climate change. In environmental management, managers may perform symbolic environmental performance in pursuit of economic benefits and good reputation (Talbot and Boiral, 2018), because image management is easier than actual performance change (Cho et al., 2012). The board as a supervisor is not directly involved in strategic decision-making and therefore cannot effectively monitor the improvement of actual carbon performance. However, some environmental strategies are also in the best interests of corporations, and managers must demonstrate good actual carbon performance to gain and maintain legitimacy (Bansal and Clelland, 2004). The board needs to strike a balance between a firm's financial and non-financial goals, resolve conflicts of interest among various stakeholders and facilitate the achievement of corporate actual carbon performance meet (Liao et al., 2015). We argue that the board's monitoring in a climate-responsible orientation is more conducive to firms' carbon strategy management, and the accumulation of monitoring experience enables the board to provide more relevant resources for the carbon strategies. This experience and knowledge can be effective in improving substantial carbon performance. Thus, we propose the following hypothesis:

Hypothesis 1: BCO has a U-shaped effect on carbon performance.

2.2 The moderating role of board carbon awareness

The efficient management of attention facilitates performance (Chan et al., 2021). Boards with climate-responsible orientation pay more attention to corporate environment-related monitoring. As resource dependence theory suggests, the board's accumulated experience and related mix of capital can increase the board's carbon awareness (Kolev et al., 2019). In the board carbon monitoring awareness, board carbon-related experience can provide managers with environmental strategic advice, and open up opportunities to improve carbon performance. The more unique resources and knowledge the board with a stronger carbon monitoring awareness acquires in relation to the environment, the more able it is to monitor managers pursuing active environmental strategies (Boh et al., 2020). In the board carbon risk awareness, boards with higher carbon risk awareness can more carefully monitor the problems faced by corporation in achieving carbon performance, and can better coordinate and deploy corporate environmental strategies. Jung et al. (2018) find that firms with greater carbon risk awareness are more likely to implement proactive carbon management strategies. Carbon risk awareness can motivate the board to better align corporate social objectives with financial objectives (Galbreath, 2018). Thus, we propose the following hypothesis:

Hypothesis 2a: Board carbon risk awareness moderates the U-shaped relationship between BCO and carbon performance.

Hypothesis 2b: Board carbon monitoring awareness moderates the U-shaped relationship between BCO and carbon performance.

2.3 The moderating role of firm reputation

Firm reputation represents the past behavior of firms and can indicate the firm's possible future financial performance to stakeholders (Davies et al., 2003). Firm reputation is an intangible strategic asset, a competitive advantage that cannot be replicated by competitors, which thus contributes to firm performance and survival (Miller and Triana, 2010). Firm reputation can position a firm to gain competitive advantages that lead to sustainable performance. A good reputation is related to firms' environmental problems (Ghuslan et al., 2021), and is a relevant outcome measure (Singh and Misra, 2021). Thus, studies on the legitimacy issues arising from reputation in the context of firm sustainability will be especially useful. Previous studies have shown that board characteristics are positively associated with the firm image and level of reputation, which foster more effective monitoring and oversight (Baselga-Pascual et al., 2018). Board's attention to monitoring management is also affected by reputational effects and greatly influences board decision-making on environmental issues (Tuggle et al., 2010). Based on the legitimacy theory, boards need to cope with external pressures and meet legal requirements to maintain and gain a good reputation, and for this purpose, symbolic and/or substantive actions will often be adopted (de Quevedo-Puente et al., 2007; Truong et al., 2021). Substantive actions minimize the firm's environmental impact and improve their environmental performance (Rodrigue et al., 2013; Berrone et al., 2017). However, improving carbon performance is a long-term process and the board cannot change the daily activities and strategic goals of the firms in a short period of time, so using symbolic environmental actions to mitigate the negative of environmental effects is popular for firms. Thus, we propose the following hypothesis:

Hypothesis 3: Firm reputation has a negative moderating effect between BCO and carbon performance.

Figure 1 illustrates the framework of theories used to test these three hypotheses, which examine the links among BCO, board carbon awareness, firm reputation, and carbon performance.

3 Current status of climate change and carbon emissions reforms in the United States

The United States is the world's most developed economy, and at the same time the economy with the highest per capita carbon emissions (Song et al., 2019). Therefore, the United States has been greatly concerned about the issue of emission reduction. The Kyoto Protocol is the first international agreement by countries to limit greenhouse gas emissions in the form of regulations. The William J. Clinton Administration signed the Kyoto Protocol in 1997, but in 2001 George W. Bush abandoned the agreement on the ground that it would harm the economy (Lord, 2005). The Paris Agreement. 2015), adopted at the United Nations Climate Change Conference in 2015, will replace the Kyoto Protocol and provide a unified arrangement for global action on climate change beyond 2020. The Paris Agreement is also second legally binding climate agreement. The Obama administration formally signed the Paris Agreement in 2016 (Clémençon, 2016). However, in 2017, the Trump administration announced its withdrawal from the Paris Agreement on the grounds that the agreement is unfavorable to the United States and advantages to other countries, and formally withdraw in 2020 (Zhang et al., 2017). Less than a year later, the Biden administration signed an executive order

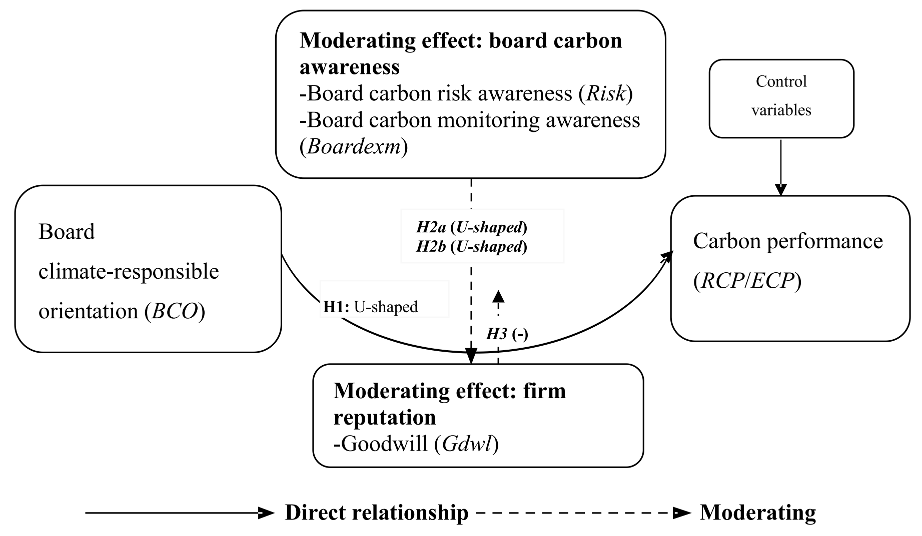

FIGURE 1
Conceptual framework.

announcing the United States' return to the Paris Agreement (South et al., 2021). We can see that the attitude of the US federal government to the emission reduction policy is constantly wavering.

While official statements from consecutive presidential administrations have expressed commitment to climate protection, actual federal efforts to reduce emissions have not gone much beyond support for research and voluntary programs (Moser, 2007). In the absence of any comprehensive federal climate change law, state and local governments' emissions reductions rely largely on market-based incentives and voluntary action. In 2005, seven US states, including Connecticut, Delaware, and Maine, signed a regional greenhouse gas initiative (RGGI) framework agreement, which formed the first market-based greenhouse gas emissions trading system in the United States. RGGI was a state-based regional partnership to combat climate change, sustaining and reducing CO_2 emissions in RGGI member states in the most economical way possible. The RGGI agreement set a cap on greenhouse gas emissions from signatory states and planned to reduce greenhouse gas emissions by 10% by 2018 compared to 2009. In 2007, California and seven other western states signed the Western Climate Initiative (WCI). WCI established an integrated carbon market that included. It was intended multiple industries and plans to be fully operational by 2015 and cover 90% of its member states' greenhouse gas emissions to reduce emissions by 15% by 2020 (Perdan and Azapagic, 2011).

In the context of the uncertain attitudes to emission reduction policy, the United States has taken a voluntary carbon emission reductions route based on the development of clean energy, using fiscal policy and carbon trading market mechanisms to promote the low-carbon transformation of firms. The United States is currently experiencing negative growth in CO_2 emissions, while the country's GDP per capita has continued to grow since2007¹. Based on the BP Statistical Review of World Energy. (2016) (Sakata et al., 2017), United States. carbon emissions increased year-on-year before 2007. Then, between 2007 and 2015, US carbon emissions decreased from 6132.4 to 5485.7 Mt per annum (Li and Su, 2017). First, the United States has successfully achieved carbon emission reduction without hindering economic development, which is worth studying and learning from (Li and Su, 2017). Second, carbon emissions reduction in the United States relies essentially on voluntary actions, which is consistent with our research data. We use second-hand data provided by CDP based on voluntary disclosures by companies, and we looked at data voluntarily disclosed by US. firms, which we argue are more reliable.

4 Research design

4.1 Data source

Our research data consists of 665 US. listed corporations reported by the Carbon Disclosure Project (CDP) during the period 2010–2019. We build a 10-year unbalanced panel dataset. The CDP report is a shared database used for recent company

1 The data source from U.S Environmental Protection Agency (EPA).

carbon emissions (Dahlmann et al., 2019). Over 80% of the world's largest 500 corporations now voluntarily provide information to the CDP (CDP Questionnaire, 2012). Although far from perfect, Kolk (2008) observes that CDP data are increasingly reliable. Disclosure includes information on senior management responsibilities for climate change. Data related to carbon emissions are constructed from firm responses to the standardized CDP questionnaire. We gather data related to firm characteristics and firm financial information from the Compustat database. According to each firm name, we determine its ticker symbol in the American Stock Exchange, and according to the ticker symbol, we merge the CDP database with the Compustat database to form our sample. A total of observations are eliminated from our sample according to the following criteria: missing carbon emissions data, incomplete or missing firm governance data, and missing financial data from Compustat. To mitigate the effect of outliers in our subsequent tests, we also winsorize all continuous financial variables at the levels of 1% and 99%.

4.2 Variables measurement

4.2.1 Dependent variables

Carbon performance (*RCP*/*ECP*). In measuring the overall effect on the carbon performance level, we employ the sum of Scope 1 and 2 emissions to estimate the relationship<sup>2</ sup>. We use two carbon performance measures. Revenues intensity performance (*RCP)* and employee intensity performance (*ECP)*. Here, we need to point out that carbon performance is the inverse of carbon emission intensity and carbon emission intensity data from the CDP report. We obtain the data from responses to the questions: 'What are your organisation's gross global Scope 1 emissions in metric tons CO_2e?' and 'Describe your organisation's approach to reporting Scope 2 emissions,' in the emissions data chapter' (CDP Global 500 Report, 2018). Revenue carbon emission intensity is defined as metric ton carbon emissions per revenue, and employee carbon emission intensity is defined as metric ton carbon emissions per full time equivalent employee. Thus, the measure of *RCP* = ln (1/revenue carbon emission intensity) and *ECP* = ln (1/employee carbon emissions intensity).

4.2.2 Independent variables

Board climate-responsible orientation (*BCO*). We define BCO as the extent to which the board of directors has climate-responsible awareness, which is measured by the board of directors as the duration of responsibility for climate change. We obtain the role of managers occupying the highest level of direct responsibility for climate change within organisations from the CDP reports, based on two questions: 'Where is the highest level of direct responsibility for climate change within your organisation?' and 'Identify the position(s) of the individual(s) on the board with responsibility for climaterelated issues.' We manually scrutinise the managers' role descriptions and identified firms that assigned the board of directors the highest level of direct responsibility for climate change within the organisation. We use the cumulative board service duration as a proxy variable for the *BCO*. We argue that the longer the board serves, the higher its climate-responsible awareness. Furthermore, we add the quadratic term variable *BC O*2 to examine the nonlinear relationship in the model.

4.2.3 Moderating variable

Board carbon risk awareness (*Risk*). We define *risk* as a dummy variable, which represents board carbon risk awareness. We obtain the data from the CDP reports, in response to the question: 'Have you identified any inherent climate-related risks with the potential to have a substantive financial or strategic impact on your business?' If there exists an awareness of the substantive financial or strategic impact of climate-related risks on the business, we assign the value of "1". Otherwise the value is "0".

4.2.4 Board carbon monitoring awareness

We define *Boardexm* as a dummy variable, which represents board carbon monitoring awareness. We obtain the data from the CDP reports, based on the question: 'Is there board-level monitoring of climate-related issues within your organization?' If a firm has board-level monitoring of climate-related issues, we assign the value of "1". Otherwise the value is "0".

4.2.5 Firm reputation

Goodwill is one of the driving forces for firms to meet legal requirements. We obtain it from the Compustat database.

4.2.6 Control variable

To control the impact of firm-specific and other governance variables on carbon performance, we control several variables, consistent with prior research (Ben-Amar et al., 2017; Haque, 2017; Bui et al., 2020; Tingbani et al., 2020; Aguilera et al., 2021; Nuber and Velte, 2021; Konadu et al., 2022). Firstly, we control for carbon attributes and board attributes including firm emission trading schemes, firm managing climate change incentives, board size and executive directors. *Scheme* is a dummy variable to indicate whether corporations participate in any emission trading schemes. *Incentive* is a dummy variable to indicate whether corporations provide incentives for

2 Scope 1 emissions are direct emissions, which refer to emissions related to the combustion of fossil fuels or the processing of chemicals and materials from sources that are owned or controlled by the company. Scope 2 emissions are indirect emissions, which refer to emissions from the generation of purchased electricity, heat or steam

managing climate change issues, including attaining targets. Both emissions reduction schemes and incentives reflect a positive attitude toward climate matters. *Bsize* is the number of directors serving on the board. Free-rider problems and conflicting decision-making in larger boards make them ineffective on climate matters (Prado-Lorenzo and Garcia-Sanchez, 2010). *Exdirector* is the total number of executive directors. Secondly, we also control firm-specific variables for firm size, capital intensity, return on assets, capital expenditure, slack resources and market-to-book ratio. *Size* shows organisational visibility, which exposes a firm to intense legitimacy scrutiny, resulting in greater responsiveness towards environmental and emission reduction issues (Datt et al., 2019). *Asset* is the ratio of firm's property, plant and equipment in total assets because firms with modern equipment are considered to have the capacity to control their emissions better than those with older equipment (Tingbani et al., 2020). *Capex* is the total capital divided by total sales. Firms with higher capital expenditure employ clean and energy efficient technologies, leading to an improvement in energy efficiency and carbon performance (Luo et al., 2012). *Roa* is determined by profit after tax, divided by total assets. Independent carbon assurance is more likely to occur in firms with higher returns on assets because such firms have more resources to afford the cost of this service (Luo et al., 2013). *Slack* captures firm's liquidity, since highly liquid firms have adequate resources that enable them to manage climate change challenges. *Mtbt* is the ratio of market-to-book value of equity. Firms with higher market-to-book ratios provide more environmental disclosure to reduce the information asymmetry between the firm and external investors (Tingbani et al., 2020). Table 1 provides all variables definition and measurement.

The tests for multicollinearity reveal the highest variance inflation factor (VIF) is 3.06, well below the suggested threshold of 10 for the risk of multicollinearity, which indicates that there are no serious collinearity problems between variables. Table A1 provides summary statistics of all variables. Table A2 presents the correlations between all variables.

4.3 Regression models

We use the following regression analysis to test the relationship between BCO and corporate carbon performance:

$$Carbon_{i,t} = \beta_0 + \beta_1 BCO_{i,t} + \beta_2 BCO^2_{i,t} + \beta_3 Control_{i.t} + \alpha_i + \delta_t + \varepsilon_{i,t} \quad (1)$$

where i indexes the firm, and t indexes the year. $Carbon_{i,t}$ is the dependent variable to reflect carbon performance, including $RCP_{i,t}$ and $ECP_{i,t}$. $BCO_{i,t}$ is an independent variable indicating board climate-responsible orientation. $BCO^2_{i,t}$ is the square of BCO. Control $_{i,t}$, including a set of time-varying control variables. α_i is firm fixed effects, and δ_t is year fixed effects. β_0 is the intercept, and $\varepsilon_{i,t}$ is the error term.

Moreover, we add the interaction items to the model to further investigate the moderating effect of board carbon awareness (*Risk*/*Boardexm*/*Gdwl*) on carbon performance. The moderating effect estimation model is as follows:

$$Carbon_{i,t} = \beta_0 + \beta_1 BCO_{i,t} + \beta_2 BCO^2_{i,t} + \beta_3 BCO_{i,t} \times Moderater_{i,t} + \beta_4 BCO^2_{i,t} \times Moderater_{i,t} + \beta_5 Control_{i,t} + \alpha_i + \delta_t + \varepsilon_{i,t} \quad (2)$$

where $Moderate_{i,t}$ including $Risk_{i.t}$, $Boardexm_{i.t}$ and $Gdwl_{i.t}$. $Risk_{i.t}$ is board carbon risk awareness. $Boardexm_{i.t}$ is board carbon monitoring awareness. $Gdwl_{i.t}$ is firm reputation.

4.4 Analytical approach

We start with the Hausman, (1978) test to examine the influence of contemporaneous correlation between the regression and the error terms. The results show a p-value of 0.0006, which is less than 1% (0.01). Thus, we reject null hypothesis and accept the alternative hypothesis. We use fixed effect models to measure the nonlinear relationship between *BCO* and carbon performance to control firm-year heterogeneity.

Although we have controlled for factors at the corporation level, there remain the possible endogeneity biases. We employ the instrumental variable (*IV*) approach and Heckman two-step procedure to alleviate endogeneity. Specifically, 'the number of firms where climate-responsible orientation boards in a certain industry (*IV*)' is used as an instrument variable, following Fu et al. (2019) and Awaysheh et al. (2020).

Furthermore, to examine the effectiveness of *BCO*, we take board carbon awareness and firm reputation as moderating variables to explore therelationship between *BCO* and carbon performance.

5 Results and analysis

5.1 Baseline regression results

Table 2 reports the regression results of *BCO* on carbon performance. We add the square of BCO to examine the nonlinear relationship. All models control for firm fixed effects and year fixed effects. Columns (1), (2), (4), and (5) do not include firm-level control variables. Columns (3) and (6) include firm-level control variables. In Columns (1) and (4), we examine the relationship between *BCO* and carbon performance. The coefficients of *BCO* are negative. And BCO is significant at the level of 5% for *ECP*. In Columns (2), (3), 5) and (6), the coefficients of *BCO* are negative and BCO^2 are positive. *BCO* and BCO^2 are all significant at the level of 1%, which indicates *BCO* has a U-shaped relationship with carbon performance. The regression results support hypothesis 1. At the early stage of boards' responsibility for climate change, their carbon management experience is not adequate. Boards might take symbolic emission reduction actions to meet shareholders' expectations and secure legitimacy. Thus, we find that the carbon performance is not ameliorated effectively. After boards hve been responsible for climate change for a while, they produce substantive action and the effect on carbon performance improve.

5.2 Addressing endogeneity

CDP is a questionnaire that is voluntarily filled out by firms. We argue that most firms willing to disclose climate information in CDP may themselves have, good climate governance systems, which leads to the problem of sample selection bias. We use Heckman is two-step method to test this biased result to verify the reliability of the conclusion. We choose the following covariables: 1) Firm size (*Emp*). The larger the firm size, the more attention if can pay to board carbon management to meet legality requirements and obtain a good firm image. 2) Whether or not the firm participates in carbon emission trade schemes (*Ets*). Boards participating in ETS are more likely to have a climate-responsible orientation to better manage carbon emissions. 3) Whether or not the firm establishes sustainability development committees (*Sdc*). The main responsibilities of the sustainable development committee are closely related to corporate sustainable development and environmental issues, so they presence shows boards with strong climate-responsible awareness. 4) Whether or not the firm has emissions reduction targets (*Target*). Emissions reduction targets are a manifestation of board climate-responsible awareness. 5) Total number of independent directors (*Indirector*). Independent directors tend to have a long-term perspective and thus tend to pursue sustainable development (Liao et al., 2015). The higher the proportion of independent directors, the higher the level of effective board monitoring of climate-responsibility. 6) Research and development investment (*Rd*). *Rd* embodies firm innovation ability, which is needed to support firm emission reduction. Firms with higher *Rd* have boards with more climate and environmental awareness. In Panel A of Table 3, the regression results for Heckman's two-step method show that the lambda is both not significant, which indicates our results have no sample selectivity bias.

Further, to alleviate the coherence bias problem, we implement the two-stage least squares (2SLS) instrumental variables approach. A valid instrument for the endogenous variable must meet two conditions: the relevance condition and exclusion restriction. The relevance condition requires a non-zero correlation between the endogenous variable and the instrument. The exclusion restriction requires that the instrument is indirectly related to the outcome variable through its effect on the endogenous variable. We use 'the number of firms with board climate-responsible orientation in a certain industry (*IV*)' as the instrumental variable. The instrumental variables are measures as follows: Firstly, when firms are considering whether to appoint the board in charge of climate-related activities, they may take the practices of firms in the same industry or the same region as a reference, so the two indicators meet the correlation hypothesis. Secondly, the number of firms that appoint the board in charge of climate-related activities in a certain industry or region has a minor impact on the carbon emissions at the firm-level, satisfying the exogenous hypothesis of instrumental variables. The regression results are reported in panel B of Table 4. The first stage regression results show that the instrumental variable (*IV*) is significantly related to the endogenous variables at the level of 1%, satisfying the correlation hypothesis. The Kleibergen-Paap rk LM statistic is 9.727 (p-value is 0.0018), which strongly rejects the unidentified null hypothesis. The Cragg-Donald Wald F statistic is 4.42, and the Kleibergen-Paap rk Wald F statistic is 4.535. All reject the weak instrumented hypothesis. In the second stage, the coefficients of *BCO* and *BC O2* are all significant at the level of 5%, which supports the instrumental variable regressions. It indicates that BCO has a U-shaped relationship with carbon performance.

5.3 Additional analysis

5.3.1 Small or medium *versus* large firms

In panel A of Table 4, we examine the impact of firm size on carbon performance. In columns (1) and (3), we use fixed effects models to estimate the regression results of small or medium corporations. In columns (2) and (4), we use fixed effects models to estimate the regression results of large firms. We find that the effects of BCO on carbon performance are significant for small or medium-sized firms. In large-sized firms, the effect is insignificant, even negative. In column (2), the coefficients of BCO^2 are negative and are significant at the level of 10%, which means *BCO* cannot effectively improve carbon performance for large-sized firms, but decreases carbons performance instead. Firstly, large-sized firms tend to emit more GHGs, which causes a burden on carbon performance management. Secondly, large-sized firm operations are intricate and the implementation results of carbon management to are slow to take effect. Thirdly, large-sized firms need to maintain profitability and pay attention to good reputations, so they are more likely to adopt symbolic carbon management to meet the legal requirements while acquiring profitability.

5.3.2 High *versus* low carbon-dependency industries

In panel B of Table 4, we examine the impact of different industry carbon-dependency on carbon performance. We

TABLE 2 Fixed-effects regression of BCO and carbon performance.

Variable	RCP			ECP		
	(1)	(2)	(3)	(4)	(5)	(6)
BCO	−0.0865 (0.0642)	−0.3231** (0.1592)	−0.5612*** (0.2001)	−0.1402** (0.0545)	−0.4355*** (0.1467)	−0.6856*** (0.2174)
BCO²		0.0233** (0.0118)	0.0473*** (0.0162)		0.0291** (0.0115)	0.0486*** (0.0181)
Scheme	−0.4019* (0.2436)	−0.4107* (0.2437)	−0.2187 (0.2456)	−0.4458** (0.2200)	−0.4568** (0.2196)	−0.1492 (0.2275)
Incentive	−0.9668*** (0.3151)	−0.9542*** (0.3122)	−1.1708*** (0.3532)	−1.3752** (0.5603)	−1.3595** (0.5557)	−1.7659* (1.0374)
Bsize	0.3608 (0.3948)	0.3653 (0.3951)	1.1593* (0.6374)	0.9919*** (0.3712)	0.9976*** (0.3708)	1.7669* (0.9859)
Exdirector	0.1743 (0.1977)	0.1693 (0.1978)	0.4486* (0.2634)	−0.0481 (0.1578)	−0.0544 (0.1566)	−0.0650 (0.2141)
Size			−3.3396*** (0.6202)			−1.7702*** (0.4800)
Asset			−2.6703** (1.1310)			−1.7946** (0.8199)
Roa			−0.2621 (0.2140)			−0.1976 (0.1472)
Capex			−0.2726 (0.4688)			−0.8711** (0.4087)
Slack			0.9441 (2.7161)			3.7113 (4.4345)
Mtbt			−1.2150*** (0.4155)			−0.5290*** (0.1702)
Firm fixed effect	YES	YES	YES	YES	YES	YES
Year fixed effect	YES	YES	YES	YES	YES	YES
N	3,287	3,287	3,287	3,287	3,287	3,287
R^2	0.8952	0.8955	0.9133	0.7315	0.7319	0.6479
F	2.3363	2.2704	5.9661	4.0045	3.5092	4.7389

Note: Standard errors are clustered at the firm level and shown in parentheses. The dependent variable in the regression is either *RCP*, and *ECP*. *RCP*, is Carbon emissions per revenues performance. *ECP*, is Carbon emissions per full time equivalent employee performance. All the regressions are controlled for firm fixed effects and year fixed effects. *$p < 0.10$; **$p < 0.05$; ***$p < 0.01$.

bounded by the median number of full-time employees and divide our sample into two subsamples. Small or medium-sized firms are below 50 percentiles and large-sized firms are above 50 percentiles. There are huge differences across firms with different carbon dependencies. Firms with high carbon-dependence are subject to higher climate change-related risks. Therefore, we might expect these corporations to provide more information about climate change-related strategies than firms with low carbon-dependency. We follow the CDP (2008) methodology and define firms in the fields of automobile and components, chemicals, forest products, gas and electrical utilities, oil and gas, mining, pipelines, precious metals, steel, and transportation as highly carbon-dependency. In columns (1) and (3), we estimate the results of firms with low carbon-dependency. In columns (2) and (4), we estimate the results of firms with high carbon-dependency. We find that the effects of *BCO* on carbon performance are significant for firms with high carbon-dependency. In firms with low carbon-dependency, the effect is insignificant. Firstly, the transformation of firms with high carbon-dependency is critical to achieving global low carbon growth. Thus, the carbon management of firms with high carbon-dependency is vital. Secondly, for firms with high carbon-dependency, carbon management is difficult, so the board of directors will focus more on corporate climate responsibility to be effective.

5.4 Robustness checks and system generalized method of moments

We perform some robustness tests to make our regression results more reliable. Firstly, we examine BCO on the composition of carbon performance. Specifically, we use Scope 1 and 2 emissions individually as alternative measures of carbon performance, including the reciprocal of scope 1 carbon emissions per revenue (*RCP1*), the reciprocal of scope1 carbon emissions per full time equivalent employee (*ECP1*), the reciprocal of scope 2 carbon emissions per revenue (*RCP2*), the reciprocal of scope 2 carbon emissions per full time equivalent employee (*ECP2*). The regression results are reported in Panel A of Table 4. Secondly, Panel B of Table 5 shows the regression results of seventy percent of the sample.

Finally, to address the concerns about potential endogeneity and reverse causality among BCO and carbon performance, we estimate a model using a dynamic two-step system generalized method of moments (GMM) panel data estimator. We have added firm dummies in all our models to control for firm-level fixed effects. In our GMM regression for BCO, we use *IV* as an endogenous variable; the specification of carbon performance (*RCP*/*ECP*) includes BCO as an endogenous variable. In all specification we use the first lags of all independent variables as instruments. The validity of the instruments is tested using the

TABLE 3 Addressing the endogeneity.

Variable	Panel A		Panel B: IV method			
Heckman two-step procedure	*RCP*	*ECP*	*RCP*	*ECP*	First stage	Second stage
			First stage	Second stage		
BCO	−3.8634*** (−3.59)	−2.8064**** (−2.72)		−6.214** (2.361)		−6.092** (2.123)
BCO^2	0.3181*** (3.14)	0.2384** (2.46)		0.572* (2.49)		0.577** (0.211)
IV_1			−2.385*** (0.476)		0.349** (0.174)	
IV^2			0.036*** (0.006)		0.045*** (0.008)	
Emp	−0.1291** (−2.37)					
Ets	0.2109** (1.90)					
Sdc	1.0497*** (7.37)					
Target	0.5227*** (4.08)					
Indirector	0.225 (1.39)					
Rd	−0.0561 (−1.43)					
Control variables	YES	YES	YES	YES	YES	YES
Firm fixed effect	YES	YES	YES	YES	YES	YES
Year fixed effect	YES	YES	YES	YES	YES	YES
N	3,440	3,440	3,440	3,440		
Lambda	−2.4358 (−1.19)	0.5157 (0.26)				
Kleibergen-Paap rk LM statistic			10.15 [0.0014]			
Cragg-Donald			4.577			
Kleibergen-Paap rk Wald F statistic			4.684			

Note: Standard errors are clustered at the firm level and shown in parentheses. The dependent variable in the regression is either *RCP*, and *ECP*. *RCP*, is Carbon emissions per revenues performance. *ECP*, is Carbon emissions per full time equivalent employee performance. *Emp* is firm size. *Ets* is carbon emission trade scheme. *Sdc* is sustainability development committee. *Target* is emissions reduction targets. *Indirector* is independent directors. *Rd* is research and development investment. All the regressions are controlled for firm fixed effects and year fixed effects. $^*p < 0.10$; $^{**}p < 0.05$; $^{***}p < 0.01$.

Hansen J statistic of overidentifying restrictions and the Arellano-Bond test of the absence of serial autocorrelation. The regression results reported in Panel C of Table 5 suggest no significant difference from the reported findings.

6 The moderating effect

6.1 The moderating effect of board carbon awareness

We consider board carbon awareness as a possible moderator variable; the results are reported in Table 6. Columns (1), generalized method of moments (2) and (3) are the regression results of fixed effect models with *RCP* as the dependent variable. Columns (4), (5), and (6) are the regression results of the year and firm fixed effect models with *ECP* as the dependent variable. Firstly, to test whether board carbon risk awareness can improve the effectiveness of board carbon management, we add the interaction terms *BCO* × *Risk* and BCO^2 × *Risk* in our model. Column (1) shows the results we see that board carbon risk awareness (*Risk*) moderates the relationship between BCO and carbon performance. The interaction term *BCO* × *Risk* is positive and is significant at the level of 1%. The interaction term BCO^2 × *Risk* is negative and is significant at the level of 5%. This indicates that board who are aware of carbon risks may reduce symbolic emission reduction actions in carbon management. However, in substantive emission reduction actions, the board weakens emissions reduction efforts, perhaps out of cautious consideration for risk. The regression results support Hypothesis 2a.

Secondly, board carbon monitoring awareness can show the extent to which the board implements effective carbon management. To test this, we add the interaction terms *BCO* × *Boardexm* and BCO^2 × *Boardexm* in our model. Columns (2) and (4) show the results, indicating that board carbon monitoring awareness (*Boardexm*) moderates the relationship between BCO and carbon performance. The interaction term *BCO* × *Boardexm* is positive and is significant at the level of 10%. *BCO* × *Boardexm* all have a significant influence on *RCP* and *ECP*. The interaction term BCO^2 × *Boardexm* is negative and is significant at the level of 1%. This indicates that board carbon monitoring awareness is mainly reflected in decreased symbolic emission reduction actions, and strict regulations on

TABLE 4 Subsample analysis for firm and industry characteristics and carbon performance.

Panel A: Firm size regression results	*RCP*		*ECP*	
Variable	**(1)**	**(2)**	**(3)**	**(4)**
	Small or medium-sized firms	**Large-sized firms**	**Small or medium-sized firms**	**Large-sized firms**
BCO	−0.8245*** (0.2624)	0.7581 (0.5120	−1.0081*** (0.0023)	0.1591 (0.2924)
BCO^2	0.0658*** (0.0208)	-0.0976* (0.0517)	0.0744** (0.0294)	−0.0315 (0.0353)
Control variables	YES	YES	YES	YES
Firm fixed effect	YES	YES	YES	YES
Year fixed effect	YES	YES	YES	YES
N	3,236	204	3,236	204
R^2	0.9197	0.8528	0.6401	0.8838
F	2.7640	1.6944	3.1195	1.026
Panel B: Carbon-dependency regression results				
Variable	***RCP***	***ECP***		
	(1)	**(2)**	**(3)**	**(4)**
	Low carbon-dependency	**High carbon-dependency**	**Low carbon-dependency**	**High carbon-dependency**
BCO	−0.1926 (0.2678)	−1.2161*** (0.1680)	−0.3386 (0.2814)	−1.5365** (0.6475)
BCO^2	0.03 (0.0236)	0.0762** (0.03)	0.0181 (0.0262)	0.1198** (0.0541)
Control variables	YES	YES	YES	YES
Firm fixed effect	YES	YES	YES	YES
Year fixed effect	YES	YES	YES	YES
N	2,216	1,224	2,216	1,224
R^2	0.7742	0.9599	0.6902	0.6370
F	2.8522	3.5012	1.9067	6.0961

Note: Standard errors are clustered at the firm level and shown in parentheses. The dependent variable in the regression is either *RCP*, and *ECP*. *RCP*, is Carbon emissions per revenues performance. *ECP*, is Carbon emissions per full time equivalent employee performance. All the regressions have controlled for firm fixed effects and year fixed effects. *$p < 0.10$; **$p < 0.05$; ***$p < 0.01$.

substantively emission reduction actions, which makes the improvement of carbon performance slow.

6.2 The moderating effect of firm reputation

Firm reputation is to meet legitimacy requirements. We add the interaction term $BCO \times Gdwl$ and $BCO^2 \times Gdwl$ in the model. Columns (2) and (4) show the results for firm reputation (*Gdwl*), it indicating that it moderates the relationship between BCO and carbon performance. The interaction term $BCO \times Gdwl$ is insignificant. The interaction term $BCO^2 \times Gdwl$ is negative and is significant at the level of 10%. This indicates *Gdwl* has a negative influence on firm substantive carbon performance. We argue that when firms excessively pursue high reputation, they tend to carry out symbolic carbon emission reduction activities that can easily be displayed to the outside world, but damage substantive carbon performance.

7 Discussion

7.1 Significance of the results

In this study, we provide empirical evidence that BCO has a U-shaped relationship with carbon performance, which is consistent with our theoretical framework. Our findings indicate that the monitoring function does not play an effective role when the board has less experience in monitoring climate issues. When the board of directors is under more legitimacy pressure, firms will implement symbolic emission reduction actions to maintain their reputation. As experience increases, the board of directors accumulates environment-related knowledge and resources to

TABLE 5 Additional robustness tests.

Panel A: The composition of carbon performance regression results

Variable	*RCP1*	*ECP1*	*RCP2*	*ECP2*
	(1)	(2)	(3)	(4)
BCO	−0.1868*** (0.0485)	−0.1629*** (0.0435)	−0.0844* (0.0435)	−0.0661* (0.0382)
BCO^2	0.0155*** (0.0043)	0.0124*** (0.0038)	0.0071* (0.0040)	0.004 (0.0038)
Control variables	YES	YES	YES	YES
Firm fixed effect	YES	YES	YES	YES
Year fixed effect	YES	YES	YES	YES
N	1,550	1,550	1,550	1,550
R^2	0.9244	0.9372	0.8590	0.8981
F	53.5320	65.3013	25.8439	37.3890

Panel B: Seventy percent of the sample regression results

Variable	*RCP*	*ECP*
	(1)	(2)
BCO	−0.853*** (0.2678)	−1.0747*** (0.3374)
BCO^2	0.066*** (0.0219)	0.0743*** (0.0275)
Control variables	YES	YES
Firm fixed effect	YES	YES
Year fixed effect	YES	YES
N	2,301	2,301
R^2	0.9262	0.6387
F	3.5381	3.6768

Panel C: GMM regression results

Variable	*RCP*	*ECP*
	(1)	(2)
BCO	−1.0461 (0.8405)	−0.9958** (0.4595)
BCO^2	0.1381** (0.0649)	0.1147*** (0.0835
Control variables	YES	YES
Firm fixed effect	YES	YES
Year fixed effect	YES	YES
N	2,408	2,408
F	2.1692	4.8402
AR (1) (*p-value*)	−2.14**(0.033)	−2.02**(0.043)
AR (2) (*p-value*)	−0.5 (0.168)	−1.41 (0.157)
Hansen J (*p-value*)	19.79 (0.955)	23.15 (0.874)
Difference-in-Hansen (*p-value*)	14.15 (0.943)	14.38 (0.938)

Note: Standard errors are clustered at the firm level and shown in parentheses. The dependent variable in the regression is either *RCP*, and *ECP*. *RCP*, is Carbon emissions per revenues performance. *ECP*, is Carbon emissions per full time equivalent employee performance. AR (1) and AR (2) are the first and second order autocorrelation of residuals, respectively; which are asymptotically distributed as N (0,1) under the null of no serial correlation. Hansen J is the test of over-identifying restrictions, asymptotically distributed as χ2 (df) under the null of instruments' validity. We tested for endogeneity using the "Difference-in-Hansen" statistic, for which the null hypothesis states that the lagged differenced instruments used for the equations in levels are exogenous in the system-GMM. *P-value* indicates that whether chi-square test is significant. All the regressions are controlled for firm fixed effects and year fixed effects. *$p < 0.10$; **$p < 0.05$; ***$p < 0.01$.

effectively monitor the firm's substantive emission reduction actions. Besides, we find that BCO has a better effect on the carbon performance of small or medium-sized and high carbon dependency firms.

Through the introduction of board carbon awareness and firm reputation, our research further explores the mechanism of BCO on carbon performance. Board carbon awareness increases the board's monitoring function on specific issues. Firstly, increased carbon risk

TABLE 6 Results for moderating effects.

Variable	RCP			ECP		
	(1)	(2)	(3)	(4)	(5)	(6)
BCO	−1.2697*** (0.3791)	−1.7852*** (0.4385)	−1.7736*** (0.4664)	−0.9964*** (0.3255)	−1.1797*** (0.4241)	−1.2827*** (0.9023)
BCO^2	0.1086*** (0.0341)	0.1616*** (0.0410)	0.1603*** (0.0429)	0.0810*** (0.0296)	0.0893** (0.0424)	0.0961** (0.0465)
BCO × Risk	0.8108*** (0.3062)	0.8983*** (0.3098)	0.8575*** (0.3195)	0.3595 (0.2869)	0.4667 (0.2899)	0.4575 (0.3022)
BCO^2 × *Risk*	−0.0719** (0.0312)	−0.0809*** (0.0313)	−0.0774** (0.0321)	−0.0381 (0.0283)	−0.0492* (0.0286)	−0.0504* (0.0293)
BCO × Boardexm		1.0390*** (0.3033)	1.1401*** (0.3097)		0.5826* (0.3427)	0.6206* (0.3749)
BCO^2 × *Boardexm*		−0.1138*** (0.0316)	−0.1197*** (0.0327)		−0.0484 (0.0416)	−0.051 (0.0456)
BCO × Gdwl			0.0832 (1.0415)			0.1078 (0.0666)
BCO^2 × *Gdwl*			−0.0113* (0.0061)			−0.0055 (0.007)
Risk	−1.8371*** (0.5693)	−1.9096*** (0.5672)	−1.8084*** (0.5973)	−0.8937 (0.5929)	−1.0380* (0.5998)	−0.9908 (0.6567)
Boardexm		0.3829 (1.0305)	0.0832 (1.0415)		1.0511 (0.8537)	1.0708 (0.8613)
Gdwl			0.6282 (0.4744)			−0.8375* (0.5033)
Firm fixed effect	YES	YES	YES	YES	YES	YES
Year fixed effect	YES	YES	YES	YES	YES	YES
N	3,322	3,322	3,322	3,325	3,325	3,325
R^2	0.9144	0.9154	0.9163	0.6483	0.6492	0.6467
F	3.6462	3.3727	3.1601	3.8536	3.9978	3.8683

Note: Standard errors are clustered at the firm level and shown in parentheses. The dependent variable in the regression is either *RCP*, and *ECP*. *RCP*, is Carbon emissions per revenues performance. *ECP*, is Carbon emissions per full time equivalent employee performance. *Risk* is board carbon risk awareness. *Boardexm* is board carbon monitoring awareness. *Gdwl* is firm goodwill. All the regressions are controlled for firm fixed effects and year fixed effects. *$p < 0.10$; **$p < 0.05$; ***$p < 0.01$.

awareness makes the board proactively identify the key risks arising from carbon-related issues and implement carbon strategies. Thus, carbon risk awareness will reduce symbolic emission reduction actions. Carbon risk awareness leads to more cautious board decision-making, so the board's carbon efficiency in substantive carbon reduction activities decreases. Secondly, we further consider carbon monitoring awareness. The Board's monitoring functions are selective, based on environmental and structural factors. The board of directors attend selectively to their monitoring function based on contextual and structural factors (Tuggle et al., 2010). We find that monitoring awareness also reduces symbolic carbon reduction actions and mitigates the effectiveness of carbon performance in substantively emission reduction actions. Thirdly, we consider the moderating effect of firm reputation. Most of the legitimacy pressure on firms is related to the pursuit of reputation. Firms that implement symbolic emission reduction actions establish a good firm image to maintain and enhance their reputation. We find that goodwill plays a negative monitoring role in corporate carbon performance, which indicates firms do engage in symbolic carbon reduction actions in pursuit of reputation.

7.2 Theoretical contributions

This paper implements multiple theoretical frameworks to make the theoretical explanation of carbon performance of board of directors more complete. Based on the two basic functions of board monitoring function and resource access functions, this paper combines the theory of agency on behalf of the monitoring function and theresource dependence theory on behalf of the resource access functions. We argue that he impact of the board of directors on carbon performance should shift from the negative linear relationship of monitoring management function to the positive linear relationship of accessible for information and resources function. This is because the agency theory leads to the symbolic emission reduction actions of the board of directors, and the resource dependence theory makes the board of directors more able to improve corporate environmental performance by accessing environment-related resources. Board function is necessary not only to meet the environmental expectations of stakeholders but also to meet the social criteria of legitimacy. Firms must increase board effectiveness in carbon-related aspects to legitimize firm activities. Thus, in our research, legitimacy theory is necessary, which is also the turning point of U-shaped relationship. What's more, we further examine the boundary effects of resource access functions and external environmental factors on carbon performance. We find that carbon awareness explained by resource dependence theory and corporate reputation influenced by legitimacy theory both affect the effectiveness of board on carbon performance. Based on the proposed theoretical framework, we explain that the U-shaped relationship between board of directors and carbon performance will be affected by carbon awareness and corporate reputation, which broadens the applicability of the theory.

7.3 Managerial contributions

Our findings offer important implications for managers and policymakers. Firstly, the increased experience of BCO will lead to better carbon performance. Based on this study, we recommend managers to actively establish the BCO and improve the board's monitoring ability. Secondly, to improve the effectiveness of the BCO monitoring function, compensation incentives, strategic carbon-reduction initiatives and other means should be implemented to facilitate BCO members' access to resources. Thirdly, for investors, invest in environmentally-friendly firms, corporations taking symbolic of carbon reduction actions without improving substantive carbon performance can confuse investors. Our results provide a reference for investors when choosing investment firms. Forthly, for policymakers, they can impose external pressure on firms through policy-making, and promoting board monitoring awareness and carbon awareness. Simultaneously, policymakers should formulate specific emission reduction requirements and evaluation criteria to measure substantive emission reduction, and prevent firms from taking symbolic emission reduction actions.

7.4 Limitations and future research

Our study is subject to several limitations that indicate potential avenues for future research. Firstly, because of data availability, our study is limited to United States. listed firms. Future, when data is available in other areas, it would be useful to extend this study to make the results more general. Secondly, this paper only considers board-level climate-responsible orientation. As climate change issues intensify, firms are increasingly inclined to appoint sub-committees to manage climate change. Future research could consider such committees' monitoring function and further refine the role of board-level monitoring. Thirdly, according to resource dependence theory, board members may access more resources of emission reduction strategies as a way to achieve effective monitoring functions. In future, the specific paths of the board's impact on carbon performance can be considered, for example, whether carbon performance is related to the large-size application of low carbon technology or internal carbon pricing.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

MX: Conceptualization; Data curation and analysis; Roles/Writing—original draft; Visualization HC: Writing—Review and editing; Supervision. QY: Data analysis; Writing—Review.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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10.3389/fenvs.2022.1043325

TABLE A1 Descriptive statistics.

Variable	Obs	Mean	Std	Min	Max
RCP	3,287	12.87	8.170	−55.81	207.3
ECP	3,287	12.25	7.557	−78.33	259.9
BCO	3,287	2.641	3.041	0	10
BCO^2	3,287	16.22	25.65	0	100
Risk	3,287	0.822	0.382	0	1
Boardexm	3,287	0.206	0.404	0	1
Gdwl	3,287	7.695	1.772	−1.302	11.89
Scheme	3,287	0.314	0.464	0	1
Incentive	3,287	0.781	0.413	0	1
Bsize	3,287	3.082	0.425	0	4.174
Exdirector	3,287	2.534	0.483	0	4.382
Size	3,287	10.09	1.414	4.830	14.78
Asset	3,287	-1.923	1.338	−9.623	−0.077
Roa	3,287	-2.502	0.801	−11.03	−0.111
Capex	3,287	-3.080	1.067	-9.398	1.528
Slack	3,287	1.045	0.0658	0.812	1.333
Mtbt	3,287	6.905	1.554	−2.872	13.84

Notes: *RCP*, and *ECP*, are measures of carbon performance. The sample period is 2010–2019. Number of firms are 575.

10.3389/fenvs.2022.1043325

TABLE A2 Correlation matrix of variables.

Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)
(1) *RCP*	1																
(2) *ECP*	0.834***	1															
(3) *BCO*	−0.049***	−0.034*	1														
(4) *BCO²*	−0.041**	−0.029*	0.951***	1													
(5) *Risk*	−0.097***	−0.101***	0.086***	0.075***	1												
(6) *Boardexm*	−0.012	−0.023	0.245***	0.334***	0.018	1											
(7) *Gdwl*	−0.175***	−0.143***	0.133***	0.134***	0.043*	0.049**	1										
(8) *Scheme*	−0.125***	−0.118***	0.109***	0.096***	0.074***	0.03*	0.249***	1									
(9) *Incentive*	−0.104***	−0.101***	0.172***	0.17***	0.235***	0.118***	0.165***	0.196***	1								
(10) *Bsize*	0.067***	0.061***	0.183***	0.153***	0.029	−0.083***	0.216***	0.142***	0.075***	1							
(11) *Exdirector*	0.092***	0.092***	0.12***	0.117***	−0.002	−0.077***	0.137***	0.134***	0.076***	0.227***	1						
(12) *Size*	−0.23***	−0.183***	0.179***	0.171***	0.011	0.039*	0.612***	0.296***	0.191***	0.311***	0.213***	1					
(13) *Asset*	−0.248***	−0.268***	0.041**	0.027	0.134***	−0.011	−0.227***	0.184***	0.055***	−0.055***	−0.113***	−0.243***	1				
(14) *Roa*	0.054***	0.032	−0.021	-0.02	−0.03	−0.049**	−0.023	0.004	0.03	−0.0110	0.065***	−0.168***	0.038*	1			
(15) *Capex*	−0.212***	−0.22***	0.089***	0.079***	0.146***	−0.001	−0.045*	0.205***	0.096***	0.023	−0.021	0.225***	0.684***	−0.141***	1		
(16) *Slack*	0.263***	0.244***	−0.123***	-0.13***	−0.093***	−0.13***	−0.269***	-0.114***	−0.118***	−0.163***	−0.027	−0.389***	−0.301***	0.226***	−0.282***	1	
(17) *Mtbt*	−0.046**	−0.055***	0.169***	0.162***	−0.081***	−0.008	0.461***	0.172***	0.155***	0.171***	0.255***	0.485***	−0.082***	0.304***	-0.067***	−0.121***	1

Notes: *RCP* and *ECP* are measures of carbon performance. *RCP* is carbon emissions per revenues performance. *ECP* is carbon emissions per full time equivalent employee performance. *BCO* is board climate-responsible orientation. *BCO²* is board climate-responsible orientation quadratic. *Risk* is board climate risk awareness. *Boardexm* is board climate monitoring awareness. *Gdwl* is firm goodwill. *Scheme* is firm emission trading schemes. *Incentive* is firm managing climate change incentives. *Size* is firm size. *Asset* is capital intensity. *Roa* is return on asset. *Capex* is capital expenditures. *Slack* is slack resources. *Mtbt* is market-to-book ratio. All the data are obtained from the CDP database and the Compustat database.

TYPE Original Research
PUBLISHED 02 December 2022
DOI 10.3389/fenvs.2022.1080809

Check for updates

OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Environmental Economics and Management, a section of the journal Frontiers in Environmental Science

RECEIVED 26 October 2022
ACCEPTED 22 November 2022
PUBLISHED 02 December 2022

CITATION
Zhang C, Tan H, Zhou M and Wang Z (2022), What was the China's spatial-temporal evolution characteristics of cross-sensitivity of ecosystem service value under land use transition? A case study of the Jiangjin, Chongqing. *Front. Environ. Sci.* 10:1080809.
doi: 10.3389/fenvs.2022.1080809

What was the China's spatial-temporal evolution characteristics of cross-sensitivity of ecosystem service value under land use transition? A case study of the Jiangjin, Chongqing

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Exploring the sensitivity of ecosystem service value (ESV) under land use transformation (LUT) is helpful to promote the rational use of regional land, improve the regional ecological environment carrying capacity, and realize the sustainable development of human beings. Using land use data of Jiangjin Chongqing from 2009 to 2019, this study measured the effect of ecological service value under land use transition in Jiangjin, and analyzed the spatiotemporal evolution characteristics of ecosystem service value based on the land use transfer matrix, change contribution rate (ESV_{ab}) and Coefficient of improved cross-sensitivity (CICS). The results showed that 1) the total ESV increased year by year, the ESV change of woodland was the largest, followed by water bodies and cultivated land from 2009 to 2019 in Jiangjin; 2) taking the Yangtze River as the boundary, the ESV in the south was higher than that in the north, but the ESV in the north and south of the Yangtze River increased to different degrees; 3) the contribution rate of forest land was the largest, the contribution rate of cultivated land and woodland was highly correlated with topography and slope, and the contribution rate of water bodies had no obvious spatial distribution characteristics from 2009 to 2019; 4) the CICS between cultivated land, woodland and other land types was higher, and mainly in the medium-high ecological sensitive areas, while the conversion between water bodies, built-up land and other land types was mainly in the medium-low ecological sensitive areas; and 5) the ecologically sensitive areas of the conversion between grassland, unused land and other land types were scattered, and the highly ecologically sensitive areas of the conversion between unused land and other land types were mainly distributed in the southern mountainous area of Jiangjin. It aims to provide important guidance for solving the contradiction between humanity and land and regional environmental problems, so as to realize the sustainable development of the region and environment.

KEYWORDS

land use transformation, ecosystem service value, change contribution rate, coefficient of improved cross-sensitivity, Jiangjin

1 Introduction

Sustainable development is the common goal of mankind and has attracted wide attention from all over the world. Sustainable development mainly includes social sustainable development, ecological sustainable development and economic sustainable development, the purpose of which is not only to relatively meet the needs of the present people, but also not to cause harm to the development of future generations (UN, 1992; UN, 2015; Bogers et al., 2022). Sustainable development emphasizes the interlinkages between social, economic and ecological dimensions (Bhaduri et al., 2016; Kumar and Banerji, 2022). Maintaining ecological sustainable development is a necessary condition for realizing sustainable development (Simpson and Jewitt, 2019). However, over the past 50 years, with rapid economic and population development, ecosystems have experienced degradation due to human-induced land-use changes, resulting in a significant reduction in environmental sensitivity and loss of biodiversity (Assessment, 2005; Singh et al., 2016). Therefore, to alleviate the relationship between economic development and ecological protection has become an important issue of great concern to researchers and policy makers.

Ecosystem services (ES) refer to the benefits that humans derive from ecosystems, which are closely related to humanity well-being and sustainable development (Costanza et al., 1997). Assessing the ESV can improve people's awareness of ecological protection, highlight the importance of natural capital, and promote the coordination of man-land relationship (Small et al., 2017). In addition, it can assess the effectiveness of ecological restoration programs and help optimize land use (Reed et al., 2017). With the rapid development and transformation of urban and rural areas in China, land use also shows a relatively strong transformation. LUT was first proposed by Grainger (1995), a scholar from the University of Leeds in the United Kingdom. As a new approach to study land use/cover change (LUCC), including the transformation of explicit and implicit land forms, affects and changes the structure and service functions of ecosystems at different scales. However, due to the one-sided pursuit of direct economic value in the past, human beings have excessively consumed natural resources in order to maximize their interests, which has caused serious damage to the ecological environment (Smith et al., 2021). Therefore, for the sake of economic benefits, LUT that is not conducive to sustainable development is common. Meanwhile, the impact of LUT on regional ecological environment will further lead to the change of ecosystem service value, and its value can quantitatively reflect the development and impact of humanity on the ecological environment in the process of economic development (Liu et al., 2022). Therefore, exploring the ESV under the transformation of land use is helpful to promote the rational use of regional land and realize the sustainable development of humanity.

Land is an important part of the earth and plays a carrier role in humanity social and economic activities (Jin et al., 2017). However, some regions ignore the non-renewable and regional differences of land resources while pursuing the improvement of economic and social benefits, which leads to the occurrence of resource and environmental problems such as rapid non-agriculture, cultivated land degradation and soil pollution, which limits the development of social economy to a certain extent (Baveye et al., 2016; Lu et al., 2021; Prabhakar, 2021). In order to solve such problems, LUT is introduced to give full play to the advantages of land resources and break the natural "dilemma" between social and economic development and land use. Therefore, land use transformation reflects the process of natural environment change and social and economic development (Long and Qu, 2018). At present, the academic research results on LUT are quite abundant, the research elements are also increasingly comprehensive, and many regular and enlightening conclusions have been produced. Lambin and Meyfroidt (2010) discussed whether the root cause of LUT was endogenous social ecological forces or exogenous social and economic factors. Quintero-Angel et al. (2021) explored LUT and landscape occupation in three historical periods in the South Pacific region of Colombia. Most of the existing researches on land use transition are carried out from the perspectives of socio-economic effect (Long and Qu, 2018), ecological effect (Asadolahi et al., 2018) and environmental effect (Asabere et al., 2020; Faiz et al., 2020). Therefore, in the global context of realizing the sustainable development goals related to land, understanding the process of regional LUT and its impact on ecological environment not only provides important guidance for solving the contradiction between man and land and regional environmental problems, but also contributes to realizing regional sustainable development.

In addition, LUT also affects ES. As a bridge between human society and ecosystem, ecosystem has become an important issue in many research fields, including ecological and environmental economics (Jiang et al., 2021). Ecosystems provide ecosystem services, tangible or intangible natural products, environmental resources, and ecological gains and losses for human beings, which can maintain human survival and promote social sustainable development (Klain et al., 2014; Li et al., 2014). Quantifying ecosystem services and analyzing their value changes is an important decision support tool for sustainable land use (de Groot et al., 2010). Therefore, the valuation of ES has become an important approach to address the global sustainability challenge. At present, the evaluation methods of ES mainly include ecological model method and benefit transfer method. Ecological modeling methods based on raw data usually require many input parameters and contain complex calculations, which are usually applied to a single service of a single ecosystem, and can only simulate the value of one or several ES, but cannot fully simulate the total ESV of an area (Notte et al., 2017). Therefore, it is only suitable for small spatial scale analysis (Remme et al., 2014). However, benefit transfer method can comprehensively assess the value of various ES in a region only based on land use data, which is suitable for ecosystem value assessment at large spatial scales (Anderson et al., 2017; Gashaw et al., 2018). Therefore, this method is widely used in the world. Using the benefit transfer method, Arowolo et al. (2018) assessed changes in the value of ecosystem services in response to land use/land cover dynamics in Nigeria. Wang et al. (2022) adopted the benefit transfer method to quantitatively assess the contribution of different LUT to ESV changes in Guizhou Province, providing valuable reference for the formulation and implementation of ecological restoration plans (ERP) and land use policies. Therefore, exploring land use change plays an important role in studying the value of regional ecological services.

Existing studies are mainly based on the perspectives of land use change (Vu et al., 2022; Xiao et al., 2022), landscape pattern (Hurskainen et al., 2019), and optimized land use structure (Gabriels et al., 2021; Ma and Wen, 2021), analyzed and discussed the relationship between different subjects and ESV from different perspectives such as county, province, city, and watershed. Wang et al. (2022) and Hoque et al. (2022) made appropriate corrections based on the previously given equivalent factor table, calculated and analyzed the characteristics of ESV combined with land use data. The research methods are relatively simple, and the results are limited to the quantitative, temporal and spatial distribution characteristics of regional ESV, and the deeper relationship analysis is shallow, which cannot reflect the comprehensive response of regional ecosystem to land use change. However, in the process of land use type transformation, the transformation of land use type will affect the structure and function of the ecosystem, thus changing the types and sizes of services provided by the ecosystem, which is one of the important factors affecting the sensitivity of the ecosystem. Therefore, LUT not only changes the structure, function and landscape pattern of land use, but also is closely related to ES, and is an important factor affecting the sensitivity of ES (Polasky et al., 2011; Dadashpoor et al., 2019; Qiu et al., 2021).

Ecological sensitivity refers to the sensitivity of the ecosystem to various natural and human activities, which can effectively reflect the possibility of ecological environmental problems when the regional ecosystem encounters disturbance (Ruhl et al., 2013). It is also an important means to study regional LUT and ES. Therefore, it is often used to measure the ecological and environmental effects of land use change (Sun et al., 2019). However, existing studies on ecological sensitivity mainly focus on the unidirectional transfer of land quantity, and less attention is paid to the bidirectional effect under LUT. Pan et al. (2012) analyzed the spatial characteristics of the sensitivity of single factor ecological problems and comprehensive ecological sensitivity, so as to provide guidance for future urban planning and development, ecological environment protection and harmonious development of society, economy and ecology. Therefore, the study of ecosystem service sensitivity is the key to the sustainable development of regional ecosystem and the comprehensive improvement of ecological environment. However, in the studies on sensitivity analysis of ecosystem services, scholars mainly used the traditional sensitivity coefficient analysis method proposed by Kreuter et al. (2001). It neglects that land use types are pluralistic. Then, some scholars tried to use land use intensity to analyze the sensitivity of ecological service value, so as to reflect the total response of ecological service value under land use change (Sannigrahi et al., 2018). However, it cannot reflect the response degree of ecological service value to each process of land use change, so it loses important information needed for land management. It can be seen that traditional sensitivity analysis methods cannot reflect the response degree of ESV to the inter-conversion process of each land use type, which has certain limitations (Liu et al., 2018). But in fact, land use transformation is a two-way street. However, in fact, LUT is bidirectional, that is, when one place is transformed into another, reverse transformation also exists (Haines-Young, 2009). However, CICS considers the net transformation between land use types, which can truly and effectively reflect the response degree of ecosystem service value to each process of land use change, and can also represent the sensitive direction, making it more practical in regional ecosystem research (Wei et al., 2022). It has been proved that the rational zoning of ecological space based on the evaluation of ecological CICS and ESV is of great significance for improving the regional ecological environment carrying capacity and promoting the harmony between man and nature. Based on this, we constructed the change contribution rate model of ESV and the CICS index, tried to explore the ESV under the background of LUT, and analyzed the sensitivity degree of ESV to LUT.

In general, this paper comprehensively reviewed the literature on ESV, in order to better clarify the innovation of this study in exploring the cross-sensitivity of ESV under LUT, and reviewed the current research progress in the field of ESV. The current research has achieved a lot of achievements, which has laid a solid foundation for this research, but there are still many subtle problems to be expanded. First of all, few scholars have conducted sensitivity measurement from the perspective of changes in ESV caused by pairwise changes in land use types, ignoring the essence of the change of ESV. Therefore, this study adopted CICS to explore the cross-sensitivity of ESV from the perspective of two-way LUT, and carried out sensitivity zoning in order to promote sustainable land use in each region. Secondly, existing studies mainly focused on the total and spatial changes of ESV caused by LUT, and paid little attention to the spatial differences in the contribution rates of change. Therefore, in order to fill the research gap on the spatial difference of contribution rate of ESV change, this study introduced the change contribution rate model to explore the spatial evolution characteristics and differences of the contribution rate of ESV change. Therefore, this study selected Jiangjin in Chongqing, where the urbanization level is rapidly increasing, as a case study. Using the data of land use transition in 2009, 2014 and 2019, we constructed the contribution rate model of ESV change and the CICS index. Then we analyzed the ESV effect of LUT in Jiangjin in recent 10 years, and pointed out the impact of LUT on the ecological value of this area. Based on the calculation results of CICS index, sensitivity zoning was carried out. It is expected to provide reference for the rapid development of urbanization, the rational use of regional land, the optimal allocation of resources, and the maximization of the value of ecosystem services in the process of conservation. Through in-depth analysis and evaluation of regional ecological sensitivity, spatial distribution can be found, which provides scientific basis for regional policies to prevent and control ecological environmental problems, which is a key link and an important way to achieve regional healthy development. In addition, we used the very helpful ArcGIS spatial analysis tool (designed to capture, analyze and represent spatial data) to analyze the spatial and temporal distribution characteristics of ESV and its cross-sensitivity. The tool can visually express the ESV and its evolution in each region, thus enabling decision makers to curb the trend towards unsustainable development in the context of land use and resource management. It can also help policy makers and authorities to better manage the region, so that cities can be optimized to promote sustainable land development in each region.

2 Research context and method

2.1 Theoretical analysis framework

The Pressure-State-Response model was developed in the late 1980s by the Organisation for Economic Co-operation and Development (OECD) and the United Nations Environment Programme (UNEP). After that, it has been widely used in the fields of resource and environment protection, land intensive use evaluation, sustainable development evaluation and so on. On the basis of PSR model, this paper added Effect research to analyze the mechanism of land use transformation (Figure 1). Population growth, urbanization and industrialization, rapid development of regional economy, adjustment of agricultural structure, environmental deterioration, market and globalization and other pressure factors form a tense man-land contradiction relationship with limited land resources, which affects the balance of land supply and demand. Under the pressure of the imbalance of supply and demand, the intensity of land use is increasing. In order to realize the protection of cultivated land and food security, the protection of built-up land and ecological protection and ecological security, it must be guided by relevant government policies. The result is the change of social production and life style, which leads to the change of land supply and demand, and then leads to the continuous reconstruction of different land use types in the region from conflict to coordination in quantity structure and spatial distribution (Zhou et al., 2022).

Based on the above analysis, the hypothesis put forward in this paper is that the direct result of LUT is the improvement and deterioration of ESV, and the change of ESV will guide the change of land use mode and land use intensity. In this paper, the total value of ecosystem services, ESV_{ab} and CICS were introduced to analyze from two dimensions of quantitative and spatial distribution characteristics. The results can be used to formulate government policies and guide more rational land use transformation.

2.2 Research methods

2.2.1 Ecosystem service value

In this paper, based on the land use status and the research methods of Costanza et al. (1997) and Xie et al. (2015), the coefficient of ESV was determined, and the relevant research results of equivalent ecological service value per unit area were referred. According to the actual situation of Jiangjin, the ESV scale per unit area of Jiangjin (Table 1) was finally determined. The evaluation method of ESV adopted the equivalent per unit area method, and the calculation formula is as follows:

$$ESV = \sum_{i=1}^{n} \left(M_i \times N_{ij} \right) \tag{1}$$

In the formula: ESV is ecosystem service value; M_i represents the area of *ith* ecosystem; N_{ij} represents the ESV per unit area of *jth* ecological service functions of *ith* ecosystem.

2.2.2 Contribution rate of ecosystem service value change

Change contribution rate can represent the influence degree of total ESV change in a period of time by different land use types of ESV change, so as to reveal the main contributing factors affecting regional ecosystem service value (Hu et al., 2020). Therefore, based on the classification of ecosystem (Table 1), we introduced change contribution rate to analyze it.

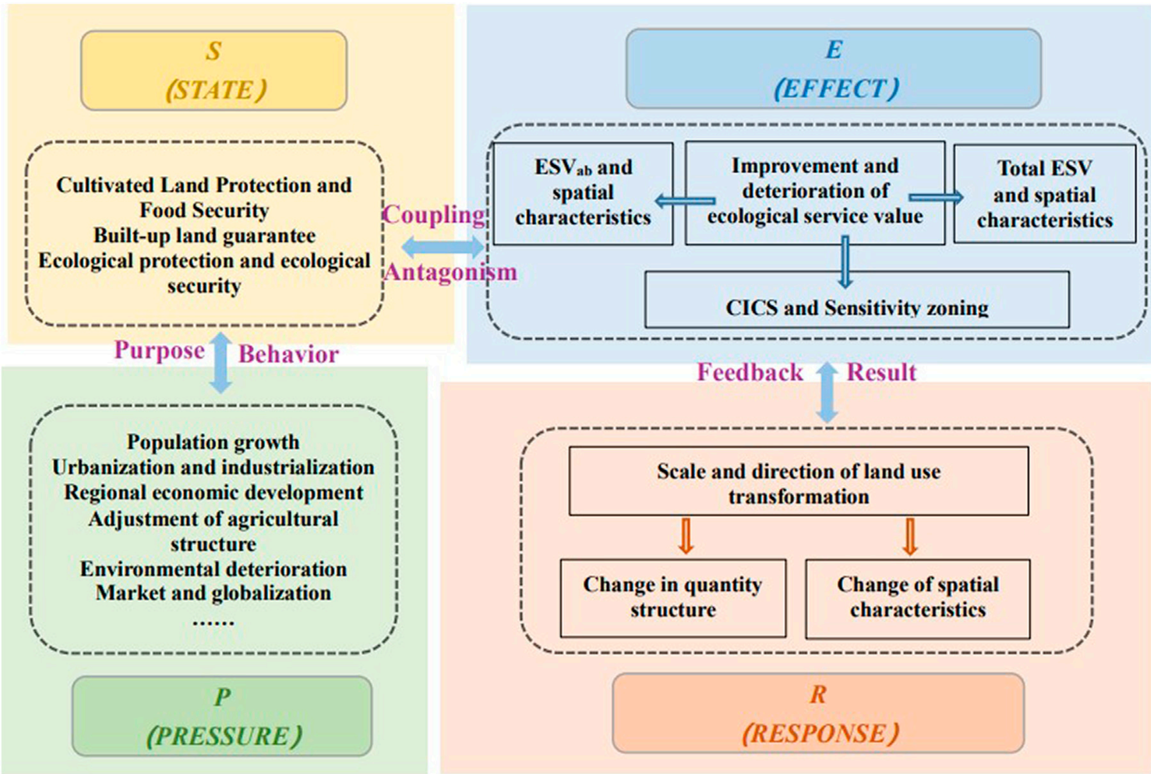

FIGURE 1
Framework diagram of land use transition mechanism based on "Pressure-State-Effect-Response" model.

TABLE 1 Value of ecosystem services per unit area in Jiangjin (RMB/hm^2/year).

Category of ecosystem	Supply service	Regulating service	Support service	Cultural service
Cultivated land	4326.26	4769.11	4340.33	204.39
Woodland	4735.05	50688.74	19348.92	3883.41
Grassland	2486.75	25105.91	9436.02	1907.64
Water bodies	31748.14	377610.50	12093.09	6438.29
Built-up land	0	510.98	136.26	34.07
Unused land	0	510.98	136.26	34.07

$$ESV_{ab} = \frac{|ESV_{ib} - ESV_{ia}|}{\sum_{i=1}^{n}|(ESV_{ib} - ESV_{ia})|} \times 100\% \quad (2)$$

In the formula: ESV_{ab} is the change contribution rate; ESV_{ia} and ESV_{ib} are ESV at the beginning and end of the study period, respectively.

2.2.3 Coefficient of improved cross-sensitivity

Coefficient of cross-sensitivity (CCS) refers to the impact of the area change of one land use type to another on the change of ESV, which is an index to characterize the response degree of ESV to the land use transformation per unit area, so as to quantify the response degree. However, since the change of land use type is often bidirectional, the essence of ESV change is the comprehensive reflection caused by the change of one land type area and the resulting change of another land type area. Although CCS meets the sensitive form, due to certain bias in the selection of the base period of the land area conversion ratio, it can only be concluded that "the ratio of the net land transfer area to the average area of the initial two classes increases by 1%, resulting in a change of ecosystem service value of several

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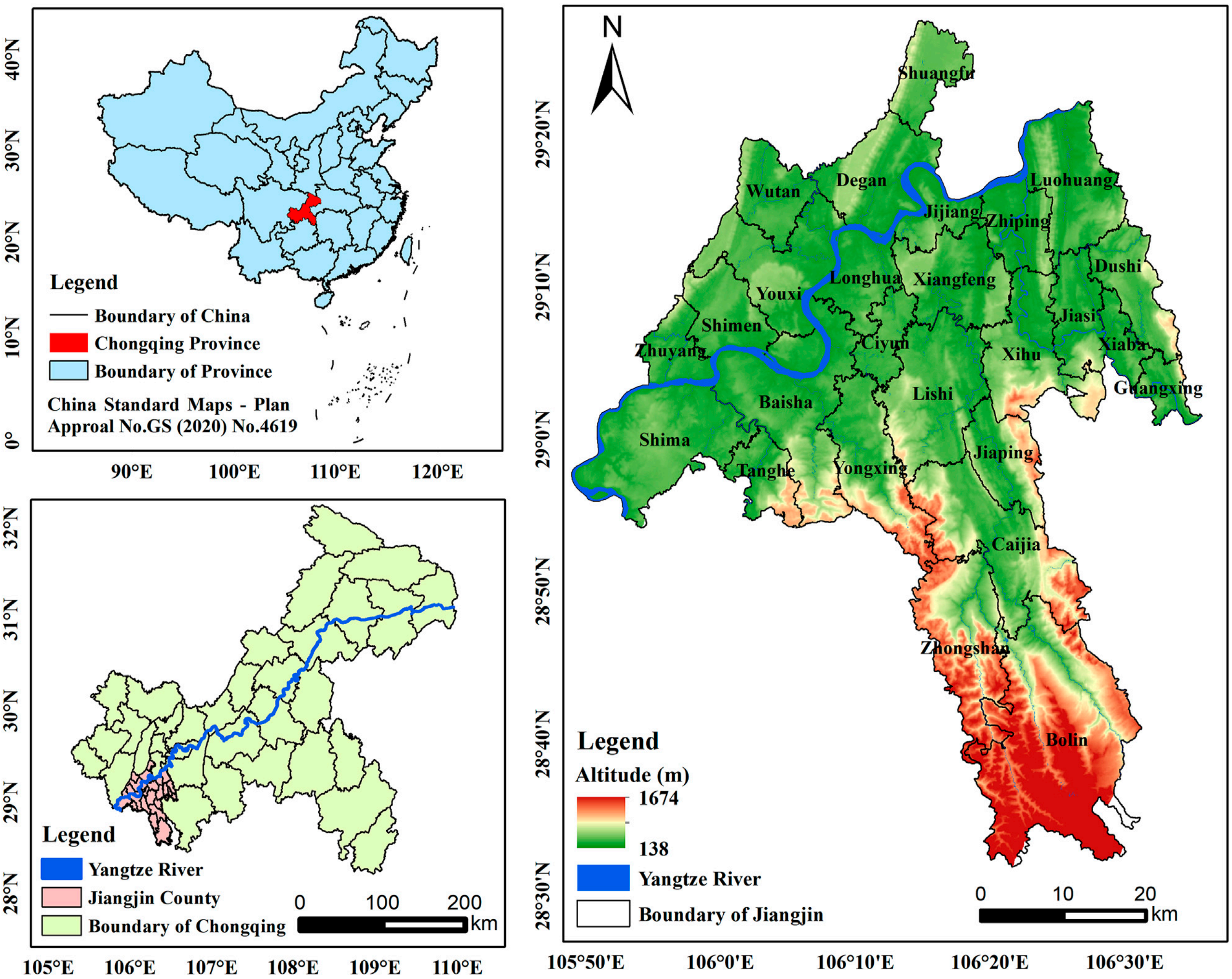

FIGURE 2
Location of study area.

percent". The calculated results are difficult to express the practical significance of the elasticity coefficient. Therefore, the CICS model is adopted in this paper. CICS refers to the extent to which a net transition between two different land use types contributes to or suppresses changes in the value of ecosystem services. It can well reflect the degree of impact of net transformation between different land classes on the change of ecosystem service value.

Based on the essence of ESV change and referring to existing related achievements (Hu et al., 2020; Wei et al., 2022), we constructed a Coefficient of improved cross-sensitivity to investigate the impact of pairwise conversion among different land use types on ecosystem service value change in Jiangjin. When the Coefficient of improved cross-sensitivity (CICS) is greater than 0, it means that the net transformation of the two types of land classes will promote the ecosystem service functions; otherwise, it will inhibit the ecosystem service functions. As the analysis object of sensitivity, the larger the absolute value of CICS is, the more sensitive ecosystem services are to the land use types of the two transitions, and the less sensitive otherwise. The CICS is as follows:

$$P_{cicski} = \frac{(V_{ck} - V_{ci})\Delta S_{ki}}{\Delta P_{ESV}} \quad (3)$$

In the formula: P_{cicski} is the cross-sensitivity coefficient of the improved bidirectional transformation between the k and i land types; V_{ck} is the modified equivalent factor (RMB/hm^2) of ESV of k land type; V_{ci} is the modified equivalent factor (RMB/hm^2) of ESV of i land type; ΔS_{ki} is the net transformation area (hm^2) between land type and land type in the j and $j-1$ year; ΔP_{ESV} is the change of ESV in j and $j-1$ year (ten thousand RMB).

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3 Study area and data sources

3.1 Study area

Jiangjin is located in the southwest of Chongqing, between 105°49′ E and 106°38′ E, and 28°28′ N and 29°28′ N (Figure 2). The landform in the area is mainly hilly and low mountains. It has prominent geographical advantages and is located in the modern metropolitan circle of Chongqing, with a rapid development momentum. By the end of 2019, the GDP of the whole region was 103.67 billion RMB, up by 8.6% year on year; Per capita GDP reached 74452 RMB, up 7.7 percent year on year. At the end of the year, the permanent resident population was 1.398 million, accounting for 69.76% of the urbanization rate. Jiangjin is located at the end of the Chongqing section of the Three Gorges Reservoir Area, and the main stream of the Yangtze River runs through the whole area from southwest to northeast. It is an important ecological barrier of Chongqing and even the whole Three Gorges Reservoir area. Due to the rich mountains and rivers resources and the large relief of the terrain, the region has created a unique "mountain-riverside" three-dimensional resource landscape, the area's mountains, forests, fields, lakes and grass ecological elements crisscross, integrated. However, with the continuous improvement of the level of economic development and the interaction between cities and cities is increasingly frequent. Especially with the continuous intervention of the follow-up project of the Three Gorges and the construction of industrial parks in recent years, the ecological environment pattern in the area has changed greatly. It is manifested in the continuous compression of ecological space, aggravated soil and water loss, increasingly serious water pollution and soil non-point source pollution, sharp reduction of biodiversity, and homogenization of ecological landscape, which seriously restrict the sustainable development of regional social economy. To deal with the contradiction between protection and development, ecology and economy has become the key problem to be solved in the future development of Jiangjin.

3.2 Data sources

The data used in this study mainly include: 1) land use types of 2009, 2014 and 2019 were interpreted based on Landsat OLI/ETM image (http://www.gscloud.cn) and Google Earth image data (https://earth.google.com). Through field investigation and careful comparison with the interpretation results of land type, the interpretation accuracy is higher than 96.3%. 2) The socio-economic data were obtained from the *Statistical Yearbook* and the *Statistical Bulletin of Jiangjin District*.

4 Result

4.1 Spatial-temporal pattern analysis of land use change

Among the land use types in Jiangjin, the cultivated land and woodland are the most widely distributed, with the cultivated land mainly distributed in the middle and the woodland mainly distributed in the southern Simian Mountain (Figure 3). In 2019, the area of cultivated land and woodland in Jiangjin was 99178 square hectometer (hm^2) and 172865 hm^2, accounting for 31.01% and 54.05% of the total area, respectively. In the same period, the proportion of grassland and water bodies is relatively small. The area of unused land is 488 hm^2, which is concentrated in Simian Mountain, accounting for only 0.15% of the total land area of Jiangjin, indicating that the land development and utilization degree of Jiangjin is relatively high, and the land reserve resources are insufficient. Affected by topography and landform, rural built-up land is scattered throughout the whole area in a star-like manner, while urban built-up land is mainly distributed in towns such as Degan, Shuangfu, Shengquan, Dingshan, Jijiang and Zhiping in the north of Jiangjin.

In order to explore the internal transformation of different regions, the spatial analysis function of ArcGIS was used to superposition the land use data of 2009, 2014 and 2019 (Figure 4 and Figure 5). According to the net area of pair conversion of land use types, it was divided into four grades: I, II, III and IV, which represented "basically no change" (0–100 hm^2), "little change" (101–200 hm^2), "great change" (201–700 hm^2) and "greatest change" (>700 hm^2), respectively. From 2009 to 2014, there were five types of grade I, which were cultivated land-woodland, cultivated land-built-up land, grassland-water bodies, water bodies-built-up land, and water bodies-unused land; there are five types in grade II, which were cultivated land-water bodies, woodland-water bodies, woodland-built-up land, grassland-built-up land, and built-up land-unused land; there were five types of grade IV, which were cultivated land-grassland, cultivated land-unused land, woodland-grassland, woodland-unused land, and grassland-unused land. The result of conversion was an increase of 252 hm^2 in cultivated land area, 222 hm^2 in woodland area, 5747 hm^2 in grassland area, 281 hm^2 in water bodies, 245 hm^2 in built-up land area and 5695 hm^2 in unused land. From 2014 to 2019, there were five types of class I, which were grassland-water bodies, grassland-built-up land, grassland-unused land, water bodies-unused land, and built-up land-unused land; in level II, there was only cultivated land-unused land; there were four types of grade III, which were cultivated land-grassland, cultivated land-built-up land, woodland-water bodies, and water bodies-built-up land; there were five types of grade IV, which were cultivated land-woodland, cultivated land-water bodies, woodland-grassland, woodland-built-up land, and woodland-unused land. The

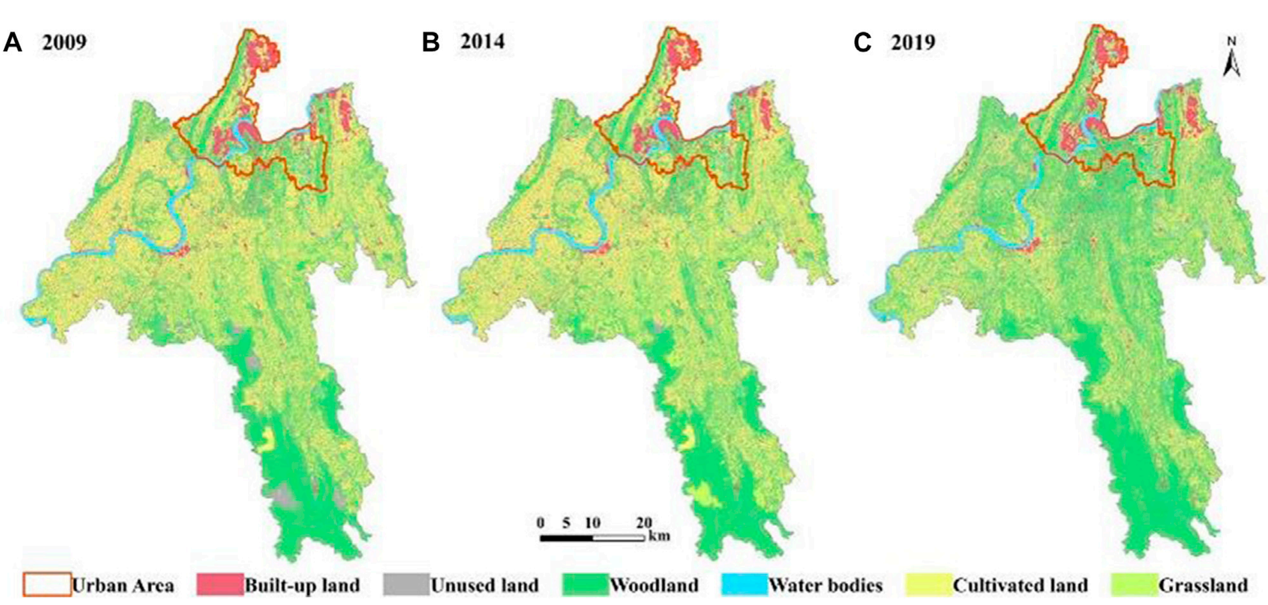

FIGURE 3
Land use of Jiangjin in 2009, 2014, and 2019. **(A)**: Distribution of land use types in Jiangjin in 2009; **(B)**: Distribution of land use types in Jiangjin in 2014; **(C)**: Distribution of land use types in Jiangjin in 2019.

conversion results in a decrease of 39049 hm^2 of cultivated land, an increase of 46661 hm^2 of woodland, a decrease of 5582 hm^2 of grassland, an increase of 4369 hm^2 of water bodies, a decrease of 5089 hm^2 of built-up land, and a decrease of 1310 hm^2 of unused land.

From 2009 to 2019, the magnitude and grade of changes in the 2009–2014 were smaller than those in the 2014–2019. Superposition the changes of the two periods showed that there were 7 types of I, which were cultivated land-grassland, woodland-grassland, grassland-water bodies, grassland-built-up land, grassland-unused land, water bodies-built-up land, and water bodies-unused land; in II, there was only one type, built-up land-unused land; there were three types of level III, which were cultivated land-built-up land, cultivated land-unused land, and woodland-water bodies; there were four types of IV, which were cultivated land-woodland, cultivated land-water bodies, woodland-built-up land, and woodland-unused land. As a result of the conversion, the cultivated land area decreased by 38797 hm^2 in 2019 compared with 2009, which was mainly converted to woodland, built-up land and water bodies; the area of built-up land decreased by 5334 hm^2, which was mainly converted to woodland and cultivated land; the unused land area decreased by 7006 hm^2, which was mainly converted to woodland and cultivated land; the woodland area increased by 46883 hm^2, the main types converted to woodland were built-up land, unused land and cultivated land; the area of water bodies increased by 4088 hm^2, the main types converted to water bodies were cultivated land and woodland; grassland increased significantly from 2009 to 2014, and then decreased significantly from 2014 to 2019, with little change in total. It showed that the development of rural tourism, the adjustment of agricultural industrial structure, the policy of returning farmland to forest and grassland, and the implementation of land development and consolidation have greatly changed the land use types in Jiangjin. However, due to the influence of natural conditions, infrastructure, social and economic development level and policy system in each region, the change degree of land use types in different regions was different.

4.2 Spatial and temporal variation analysis of ESV

4.2.1 Analysis of changes in total value of ecosystem services

According to Eq. 1, the total ESV of Jiangjin and villages in 2009, 2014 and 2019 were calculated (Table 2 and Figure 6). The value of ES in Jiangjin in 2009, 2014 and 2019 was 17.796 billion RMB, 17.916 billion RMB and 22.702 billion RMB respectively, showing an increasing trend year by year. Based on the research of Li and Chen (2021), we used the natural break point method in ArcGIS software to divide the total ESV of each village into four grades: I, II, III and IV, respectively representing the system development states of “bad”, “poor”, “fair” and “good” (Figure 6), and counted the occurrence frequency of villages of different grades. From 2009 to 2014, there were 215 ESV

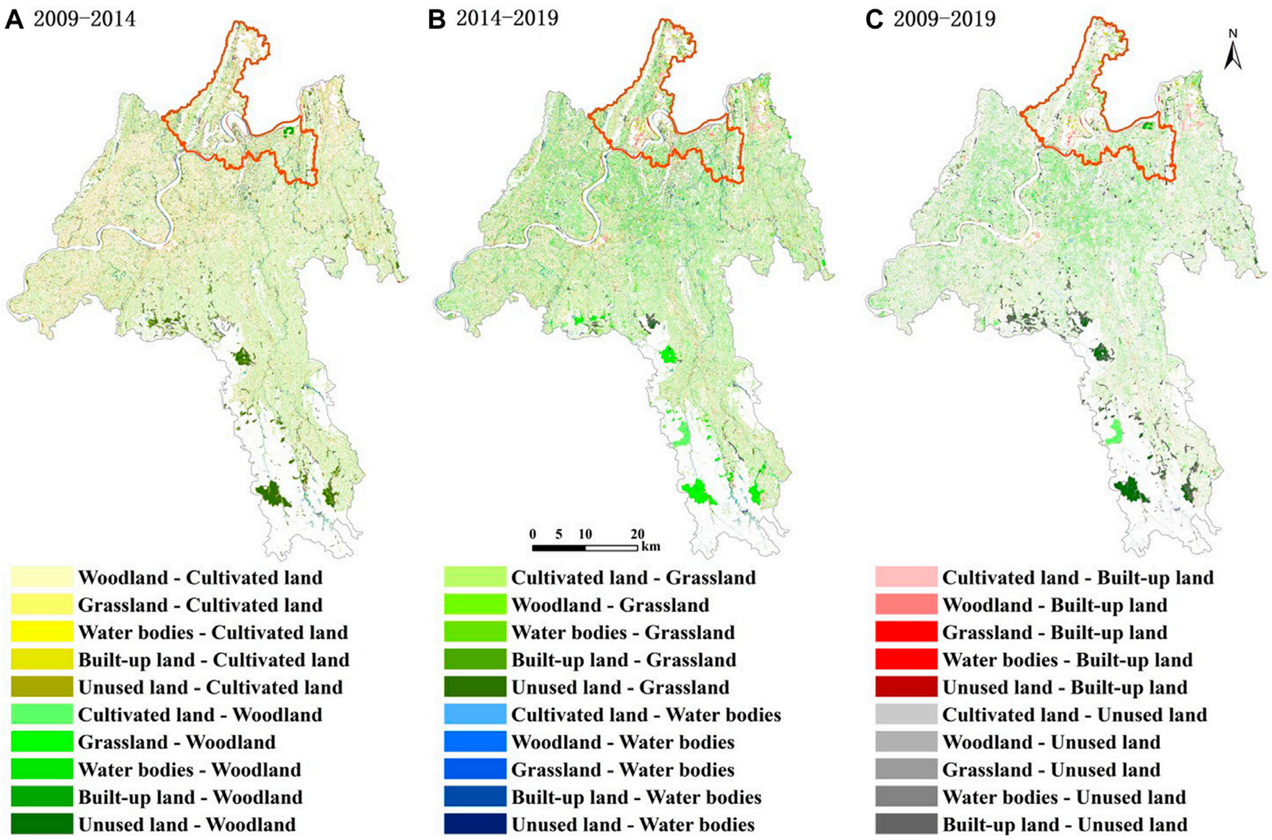

FIGURE 4
Land use changes in Jiangjin during 2009–2019. **(A)**: land use changes in Jiangjin from 2009 to 2014; **(B)**: land use changes in Jiangjin from 2014 to 2019; **(C)**: land use changes in Jiangjin from 2009 to 2019.

grades that did not change, 5 of them increased, and only 2 of them decreased. From 2014 to 2019, there were 170 ESV grades that did not change, 49 of them increased, and 3 of them decreased. In general, the number of villages with good ESV did not increase significantly, only 3 in 2009 increased to 5 in 2019, but the number of villages with poor ESV decreased rapidly, from 145 in 2009 to 104 in 2019, a decrease of nearly 30%. The value of ecosystem services in Jiangjin showed a good trend, with an increase in high grade villages and a significant decrease in low grade villages.

From the perspective of spatial distribution, the areas with good ESV were mainly concentrated in the southern Simian Mountain and the central agricultural concentration areas. Taking the Yangtze River as the boundary, the ESV of the southern part of the Yangtze River was better than that of the northern part, but the ESV of the northern and southern parts of the Yangtze River increased to different degrees. The central and southern regions have relatively high terrain, which is due to the implementation of the policy of returning farmland to forest or grassland and land development and consolidation. A large area of unused land, grassland and cultivated land was transformed into woodland, and the value of ES increased greatly. The east and west sides of the central part of the relatively flat terrain, cultivated land concentration, Jiangjin is the traditional main grain production areas. However, due to the adjustment of agricultural industry structure and the development of rural tourism, part of cultivated land was transformed into woodland, so the ESV increased slightly. Jiangjin urban built-up area is distributed in the north, which is also the main expansion area of Jiangjin town. Land use was transformed to built-up land, and the landscape pattern of land use gradually tended to be homogenized. The value of ecosystem services did not change much, and some villages showed a decline. In general, the ESV of Jiangjin did not show obvious urban-rural division, and the ESV of Jiangjin showed great spatial differences in the urban area, the urban-rural fringe and the rural area.

4.2.2 Analysis of contribution rate of ESV change

From 2009 to 2019, the woodland area in Jiangjin increased by 46882 hm^2, the water bodies increased by 4088 hm^2, the

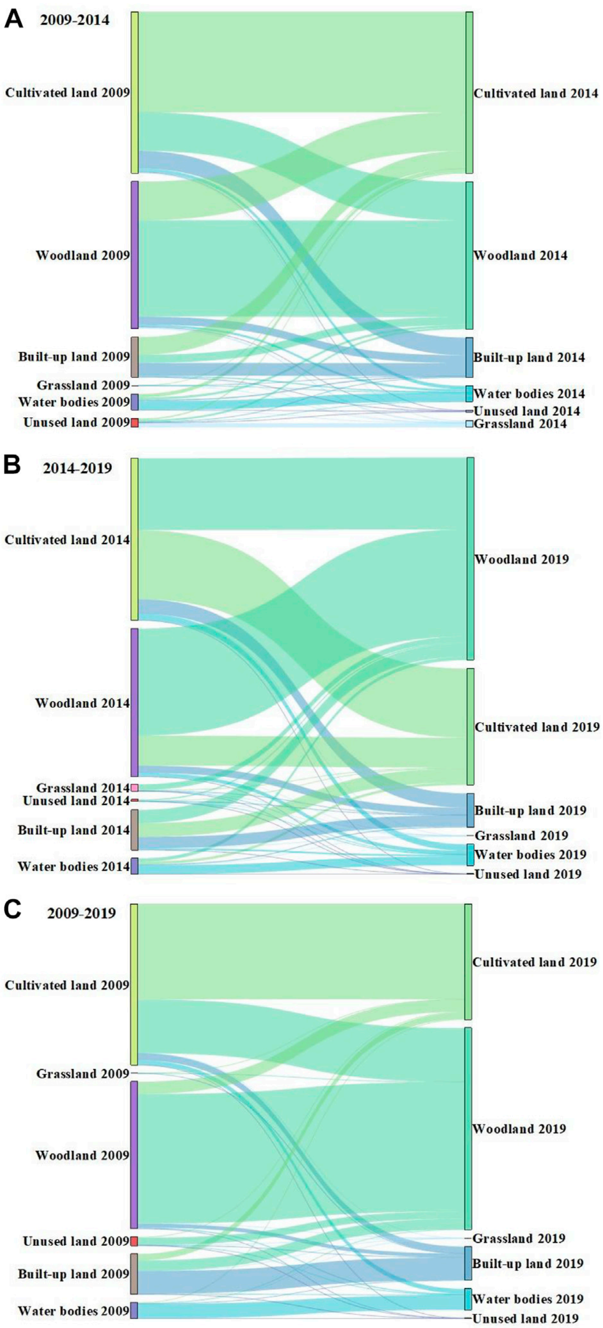

FIGURE 5
Mulberry map of land use change in Jiangjin during 2009–2019. **(A)**: the area of land use change in Jiangjin from 2009 to 2014; **(B)**: the area of land use change in Jiangjin from 2014 to 2019; **(C)**: the area of land use change in Jiangjin from 2009 to 2019.

cultivated land area decreased by 38798 hm^2, the built-up land area decreased by 5334 hm^2, the unused land area decreased by 7006 hm^2, and the grassland area did not change much (Figure 7). From 2009 to 2019, the largest increase of ecological service value in Jiangjin was woodland, which was 3.688 billion RMB; the second was water bodies, with an increase of 1.749 billion RMB; cultivated land was reduced by 529 million RMB; there was little change in built-up land, unused land and grassland (Table 2).

The contribution rate of the change of ESV (hereinafter referred to as "contribution rate") of each land use type from 2009 to 2019 was calculated, it was found that the contribution rate of woodland was the largest, accounting for 61.66%; the second was water bodies, the contribution rate was 29.25%; The third is cultivated land, the contribution rate was 8.85%; finally, the contribution rate of built-up land, unused land and grassland was slight. Woodland, water bodies and cultivated land were the main contributing factors of ESV change in Jiangjin. The data showed that the ESV per unit area of built-up land and unused land was not high, and the change of grassland transformation was not large, resulting in large changes in the area of these three land categories but little change in the value of ecological services. The overall change trend of contribution rate is similar to the change quantity, and the change of each area is the fundamental reason for the change of ESV in Jiangjin.

The contribution rate of ESV of different types of land use is also different in spatial distribution. The contribution rate of cultivated land was 0.31%–25.72%, the contribution rate of woodland was 1.38%–87.18%, and the contribution rate of water bodies was 4.98%–97.21%. The contribution rate of cultivated land and woodland was highly correlated with topography and slope; the contribution rate of cultivated land was higher in villages with lower topography and smaller slope; the contribution rate of woodland was higher in villages with higher topography and higher slope; the contribution rate of water bodies has no obvious spatial distribution.

4.3 Cross-sensitivity analysis of ESV

Cross-sensitivity considers the net conversion between different land types and assumes that when one land type changes to other land types, the remaining land types remain unchanged. Therefore, in a certain period of time, the difference of area change between each two types of land will lead to the difference of the change rate of ecosystem service value. In addition, because the net conversion between different classes is also different, the cross-sensitivity results of different conversion types show different characteristics. Based on the calculation results of CICS, the analysis was carried out from quantitative characteristics and spatial characteristics.

4.3.1 Quantitative analysis of cross sensitivity of ESV

In order to further explore the ESV of Jiangjin, we calculated the corresponding CICS for 15 pairwise conversion types of 6 land types in three periods of 2009–2014, 2014–2019 and 2009–2019 (Figure 8).

TABLE 2 Changes of ESV in Jiangjin during 2009–2019 (million RMB/hm²/year).

Land use type	ESV			ESV change		
	2009	2014	2019	2009–2014	2014–2019	2009–2019
Cultivated land	1882	1885	1353	3	−533	−529
Woodland	9909	9927	13597	17	3670	3688
Grassland	0	224	7	224	−217	6
Water bodies	5976	5856	7725	−120	1869	1749
Built-up land	23	23	20	0	−3	−4
Unused land	5	1	0	−4	−1	−5
Total	17796	17916	22702	120	4785	4906

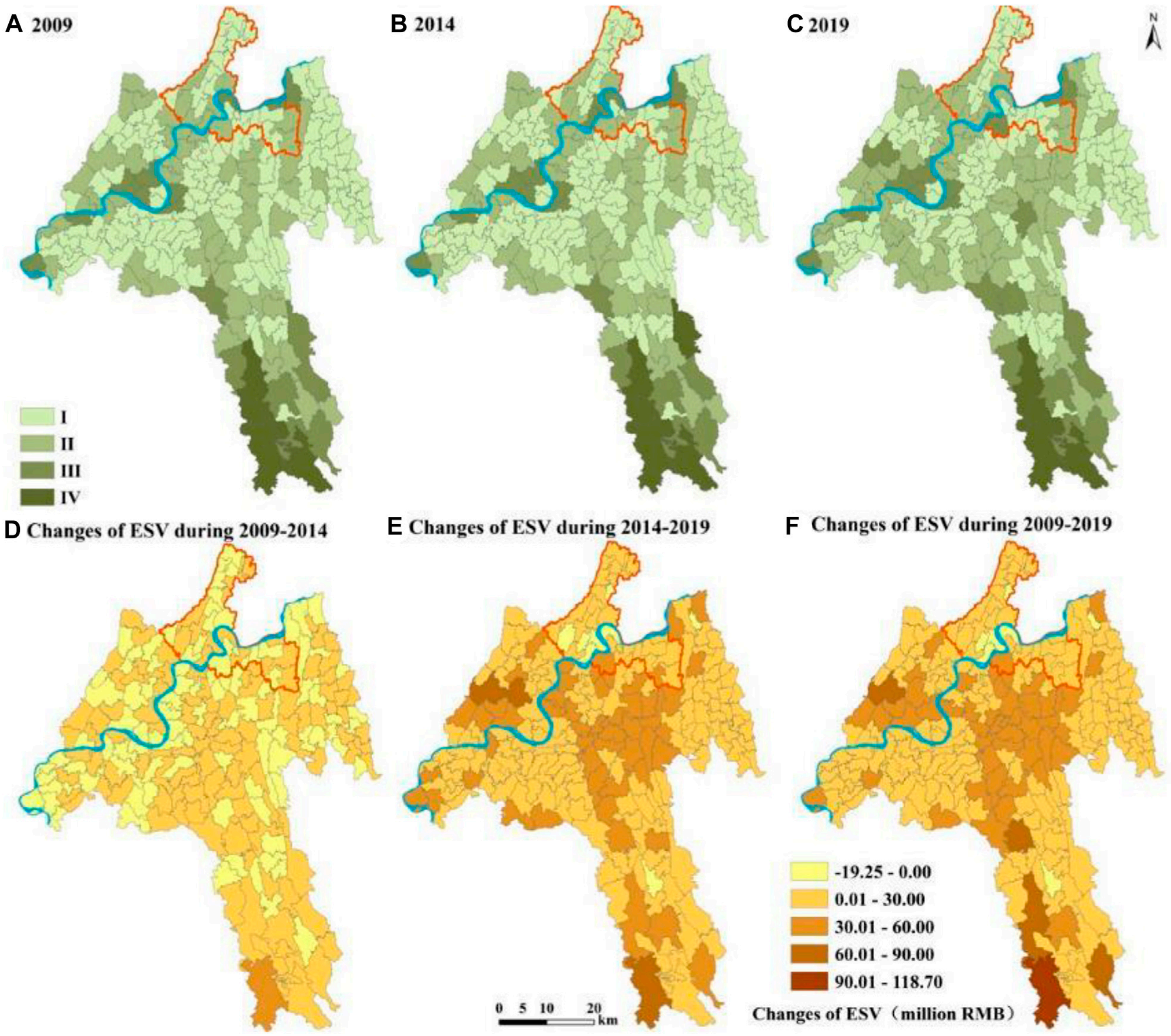

FIGURE 6
Spatial and temporal changes of ecosystem service in jiangjin from 2009 to 2019. **(A–C)** represent the grades of ecosystem service value in Jiangjin in 2009, 2014 and 2019, respectively; **(D)**: change of ecosystem service value in Jiangjin from 2009 to 2014; **(E)**: change of ecosystem service value in Jiangjin from 2014 to 2019; **(F)**: change of ecosystem service value in Jiangjin from 2009 to 2019.

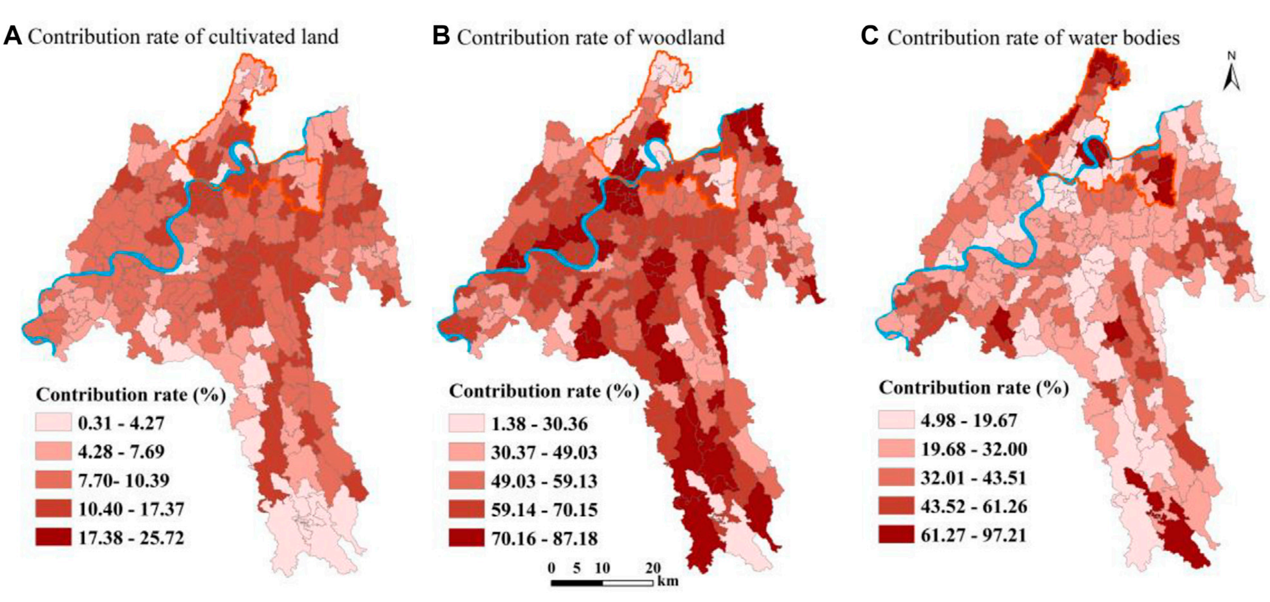

FIGURE 7
Contribution rate of land use ecosystem service value change in Jiangjin from 2009 to 2019. **(A)**: contribution rate of cultivated land from 2009 to 2019; **(B)**: contribution rate of woodland from 2009 to 2019; **(C)**: contribution rate of water bodies from 2009 to 2019.

Cross-sensitivity between cultivated land and other land types. At the beginning of the study, the conversion of cultivated land to grassland and woodland was net transfer out, and the conversion of built-up land and unused land to cultivated land was net transfer in, which increased the ESV, the CICS were 0.1608, 0.0028, 0.0095 and 0.0889, respectively, indicating that the transformation of land type promoted the change of ESV. In the later stage of the study, the conversion of cultivated land to woodland and water bodies was net transfer out, the conversion of unused land to cultivated land was net transfer, which increased the ESV and CICS were 0.4873, 0.2862 and 0.0004, respectively; also, a certain amount of cultivated land was converted to built-up land and grassland to cultivated land, which reduced ESV, and CICS were −0.0018 and −0.0033, respectively, indicating that the transformation of land type promoted the change of ESV much more than inhibited it.

Cross-sensitivity between woodland and other land types. At the beginning of the study, the conversion from woodland to grassland was net transfer out, the conversion from water bodies to woodland was net transfer in, which reduced ESV, with CICS values of -0.4136 and -0.2933, respectively, indicating that the transformation of land type inhibited the change of ESV; however, the conversion of built-up land and unused land to woodland was a net transfer, which increased the ESV, and the CICS were 0.1288 and 0.7583, respectively, indicating that the conversion of land type promoted the change of ESV. In the later period of the study, a large amount of grassland, built-up land and unused land converted to woodland into net transfer, and a small amount of woodland converted to water bodies into net transfer, which increased the ESV, and the CICS were 0.0397, 0.0849, 0.0171 and 0.0185, respectively, indicating that the transformation of land class promoted the change of ESV.

Cross-sensitivity between grassland and other land types. At the beginning of the study, the conversion of woodland and water bodies to grassland was net transfer, which reduced ESV with CICS of -0.4136 and -0.1601, respectively; however, in the later period of the study, the conversion of grassland to woodland and water bodies was a net outflow, which increased the ESV and CICS to 0.0397 and 0.0061, respectively; the results showed that the transformation of land type inhibited ESV in the early stage and promoted ESV in the later stage, and the two were basically neutralized. At the beginning of the study, the conversion of cultivated land, built-up land and unused land to grassland was net transfer, which increased the ESV with CICS of 0.1608, 0.0428 and 1.1272, respectively; In the later period of the study, the conversion of grassland to cultivated land and built-up land was a net outflow, which reduced the ESV and CICS to -0.0033 and -0.0007, respectively; This indicated that the terrestrial transition promoted ESV changes in the early stage and inhibited them in the later stage, and they were basically neutralized.

Cross-sensitivity between water bodies and other land types. At the beginning of the study, except that the conversion from unused land to water bodies was net transfer (0.0355); the conversion of water bodies to other land types was net

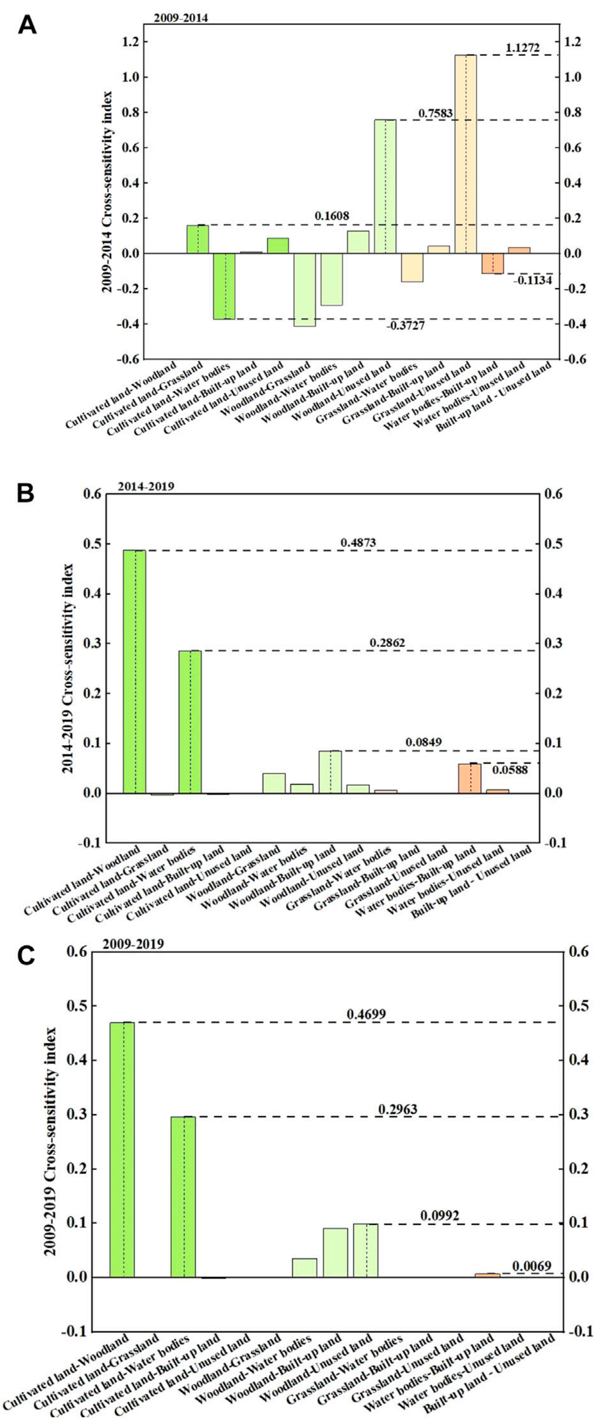

FIGURE 8
Cross-sensitivity index of ecosystem service value in Jiangjin during 2009–2019. **(A)**: cross-sensitivity of ecosystem service value from 2009 to 2014; **(B)**: cross-sensitivity of ecosystem service value from 2014 to 2019; **(C)**: cross-sensitivity of ecosystem service value from 2009 to 2019.

transfer out, which reduced ESV, with the CICS were cultivated land (−0.3727), woodland (−0.2933), grassland (−0.1601) and built-up land (−0.1134). In the later period of the study, the conversion of water bodies to unused land and built-up land was net transfer (0.0068, 0.0588); the conversion of other land types to water bodies was also a net transfer, which increased ESV, with the CICS ranked as cultivated land (0.2862), woodland (0.0185), and grassland (0.0061).

Cross-sensitivity between built-up land and other land types. There was no sensitivity for built-up land and unused land. At the beginning of the study, except for a small number of water bodies, the conversion to built-up land was net transfer (−0.1134); the conversion of built-up land to other land types was a net transfer, resulting in an increase in ESV, and the CICS were woodland (0.1288), grassland (0.0428) and cultivated land (0.0095). In the later period of the study, the conversion of cultivated land and grassland to built-up land was a net transfer, which reduced the ESV slightly, and the CICS were −0.0018 and −0.0007 respectively; however, the conversion of built-up land to woodland and water bodies was a net transfer out, which greatly increased the ESV, and CICS were 0.0849 and 0.0588, respectively.

Cross-sensitivity between unused land and other land types. During the whole study period, the conversion of unused land to other land types was net transfer out, which increased ESV. At the beginning of the study, the CICS were grassland (1.1272), woodland (0.7583), cultivated land (0.0889), and water bodies (0.0355). In the later period of the study, the sensitivity of unused land-woodland (0.0171) was high, while the sensitivity of unused land-water bodies (0.0068) was low. The sensitivity of unused land-water bodies and unused land-grassland was lack.

Throughout the whole study period from 2009 to 2019, the transition highly sensitive to ESV change was ranked as cultivated land-woodland (0.4699) and cultivated land-water bodies (0.2963) according to the size of CICS. The transitions that were moderately sensitive to ESV changes were woodland-unused land (0.0992), woodland-built-up land (0.0911), woodland-water bodies (0.0353). The transitions with low sensitivity to ESV changes were water bodies-built-up land (0.0069), cultivated land-unused land (0.0016), cultivated land-built-up land (−0.0011). The transitions that were not sensitive to ESV changes included water bodies-unused land, transformation of grassland and other land types, and built-up land-unused land.

4.3.2 Cross-sensitivity partitioning of ESV

According to the cross-sensitivity response results of ESV under LUT in Jiangjin. ArcGIS natural break point method was used for grade division, we obtained the cross-sensitivity partition from 2009 to 2019 (Figure 9), analyzed the spatial distribution characteristics of the cross-sensitivity of ESV value in Jiangjin.

From 2009 to 2019, the cross-sensitivity of conversion between cultivated land and other land types in Jiangjin was at a medium-low level on the whole, and the low ecological sensitive areas were mainly distributed in the west of Jiangjin.

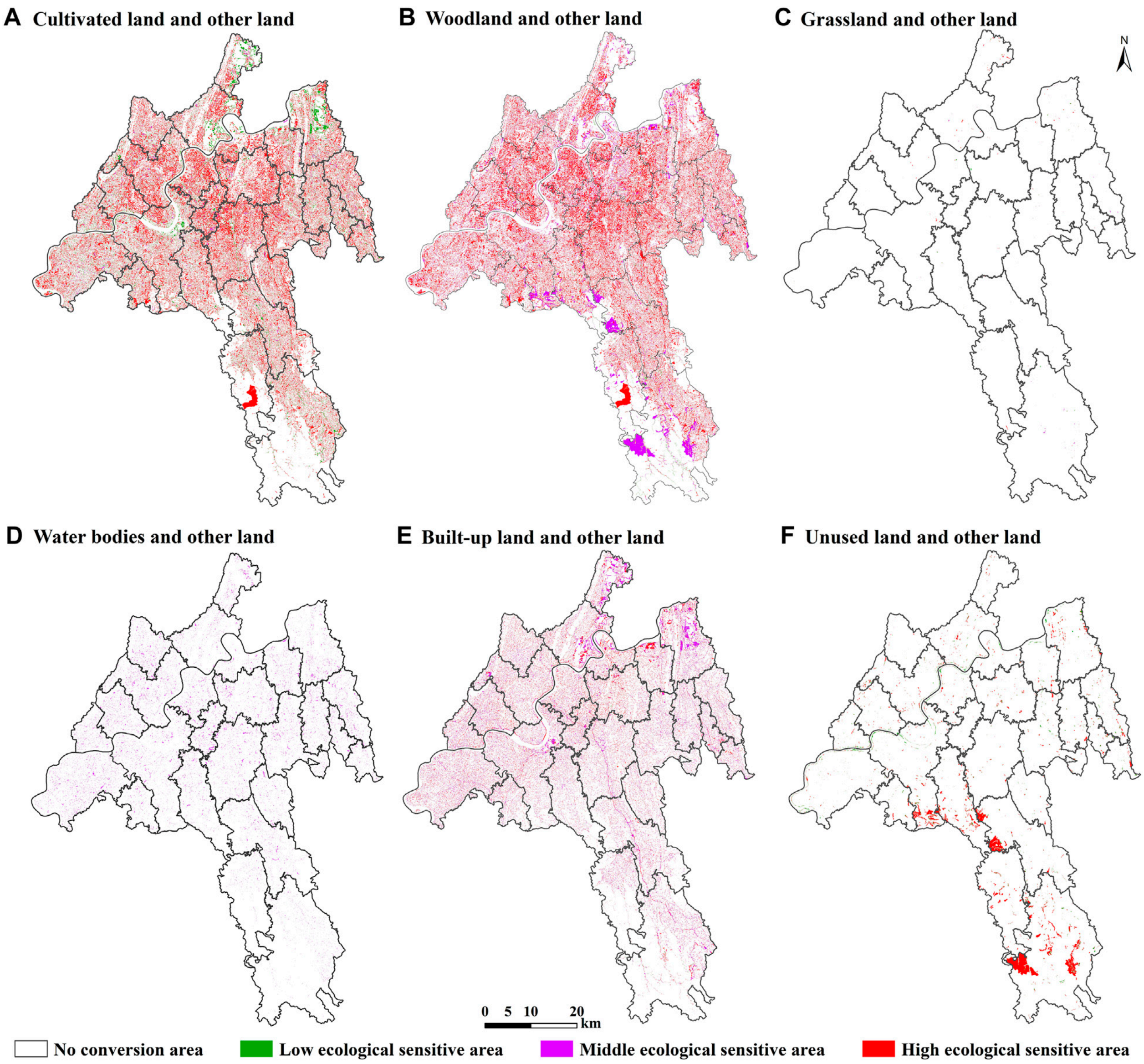

FIGURE 9
Cross-sensitivity zoning of ecosystem service value in Jiangjin from 2009–2019. **(A–F)** represent the cross-sensitivity zoning of cultivated land and other land, woodland and other land, grassland and other land, water bodies and other land, built-up land and other land, unused land and other land, respectively.

The cross sensitivity between woodland and other land types was at a medium level, and the low ecological sensitive areas were mainly distributed in the northern and southern mountains of Jiangjin. There were few net conversions between grassland and other land types, so the cross-sensitivity zones of these conversion types were scattered, and most of them were no net conversions. The low ecologically sensitive areas were mainly distributed in the south and north, the high ecologically sensitive areas were mainly concentrated in the east, and there were almost no ecologically sensitive areas in the west.

The cross sensitivity of the conversion between water bodies and other land types was high. These high ecologically sensitive areas were dominant in Jiangjin, but there were also many areas in the north and south of Jiangjin that belong to the low ecologically sensitive areas. The low ecological sensitive areas in the south were mainly distributed in the Simian Mountain, and the low ecological sensitive areas in the north were distributed along the Yangtze River. The conversion between built-up land and other land types was mostly middle and high ecological sensitive area. The low ecological sensitive areas were mainly distributed in the south of Jiangjin, the middle ecological sensitive areas were mainly in the west, and the high ecological sensitive areas near the main city area in the north were relatively more concentrated. The net conversion between the unused land and other land types was less, and the ecologically sensitive areas also showed sporadic distribution. However, these conversion types were more ecologically sensitive areas than grassland and other land types, mainly showing high ecologically sensitive areas, and concentrated in the south and north of Jiangjin along the Yangtze River.

5 Conclusion and discussion

5.1 Conclusion

In this study, three phases of Jiangjin land use data from Landsat OLI/ETM image data and Google Earth image data were selected. We combined the spatial analysis method of ArcGIS software to analyze the spatial and temporal changes of ESV, the contribution rate of LUT to the change of ESV, and the impact of cross-sensitivity in the region. In addition, partition was conducted according to the cross-sensitivity measurement results, and the following results were obtained:

1) In terms of land use transformation, cultivated land, built-up land and unused land decreased significantly, while woodland and water bodies increased significantly from 2009 to 2019 in Jiangjin. The area of grassland increased first and then decreased, with a significant increase from 2009 to 2014 and a significant decrease from 2014 to 2019, with little change in total.
2) In terms of the spatial and temporal changes of ESV, the total amount of ESV in Jiangjin from 2009 to 2019 was 17.796 billion RMB, 17.916 billion RMB and 22.702 billion RMB, respectively, showing an increasing trend year by year. Among the ESV types, woodland > water bodies > cultivated land > built-up land > grassland. From the perspective of time series, the ESV of woodland changed the most from 2009 to 2019, which increased by 3.688 billion RMB; secondly, water bodies and cultivated land increased by 1.749 billion RMB and decreased by 529 million RMB respectively; finally, there was little change in built-up land, unused land and grassland. From the perspective of spatial distribution, the areas with good ESV in Jiangjin were mainly concentrated in the southern Simian Mountain and the central agricultural concentration area. The ESV in the southern part of the Yangtze River was better than that in the northern part of the Yangtze River. In addition, the ESV of Jiangjin did not show obvious urban-rural division, and the ESV of Jiangjin showed great spatial differences in the urban area, the urban-rural fringe and the rural area.
3) The contribution rate of woodland change from 2009 to 2019 was the largest in Jiangjin, reaching 61.66%; secondly, the contribution rate of water bodies and cultivated land was 29.25% and 8.85%, respectively; the contribution rate of cultivated land and woodland is highly correlated with topography and slope, while the contribution rate of water bodies has no obvious spatial distribution characteristics.
4) In terms of cross-sensitivity of ESV, among the 15 conversion types of 6 land types in Jiangjin, the CICS between cultivated land, woodland and other land types was higher, and the response degree of ESV to these conversion types was more obvious. The conversion between built-up land and unused land has almost no effect on the change of ESV. Because the net conversion between grassland and unused land and other land types is less, the ecologically sensitive areas of these conversion types are mostly scattered, and it is difficult to form a large area of concentrated ecologically sensitive areas.

5.2 Discussion

The research on ESV based on LUT has been extensive, but there is still a need for innovation in methods. In order to expand the research perspective and ideas and deepen the research results of this paper, the adoption of research methods and main conclusions in this paper were further discussed.

In this paper, change contribution rate and CICS were introduced to comprehensively analyze the effects of ESV under LUT, which enriches the research methods. In order to reveal the ecosystem effect caused by regional land use change. Wang and Cao (2021), Wang et al. (2020) and Yi et al. (2016) constructed the contribution rate model. However, only quantitative characteristics of contribution rate were measured and analyzed. In order to further investigate the spatial distribution differences of contribution rate, this paper also analyzed the impact of topography and slope on contribution rate.

The CICS used in this paper made the results more realistic. Wang et al. (2020) analyzed the sensitivity of ESV to coefficient changes by constructing sensitivity index. However, the impact of the transformation between different land use types on the value of ecosystem services was not considered. Because the change of land use type is always bidirectional, the essence of the change of ESV is the comprehensive reflection caused by the change of one type of land area and the resulting change of another type of land area. Therefore, this paper adopted CICS to explore the cross-sensitivity of ESV from the perspective of two-way LUT, and conducted sensitivity zoning in order to promote sustainable land use in each region. It can not only reflect the influence degree of net conversion between different land types on the change of ESV, but also provide a more intuitive scientific basis for optimizing the regional land use pattern and regulating the LUT. This brings a new perspective for the study of ESV.

According to the empirical results of this paper, the ESV of Jiangjin increased year by year. This is consistent with the study of

Zhou et al. (2022). Since 2000, when the Three Gorges Dam was continuously closed for water storage, the national and local governments have adopted and implemented a series of policies, plans and ecological projects to protect the ecological environment in the region. As Chongqing accelerated the construction of the ecological barrier of the Three Gorges Reservoir, one of the main reasons for the significant increase of the ESV in Jiangjin was the effective implementation of the policy of returning farmland to forest and land development and consolidation. The large increase of woodland area increased the total ESV in this area. The value of ecosystem services per unit area of water bodies was the largest, and a large area of cultivated land and woodland were converted to water bodies, which increased the value of ecosystem services, and the value of ecological services was sensitive to these conversion types. On the basis of the research conclusions of Zhao et al. (2022), it is proved that the conversion from land types with lower ecological value equivalent factors to land types with higher ecological value equivalent factors would affect the regional ecological environment quality, but such conversion showed positive effects.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: The data used in this study mainly include: 1) land use types of 2009, 2014 and 2019 were interpreted based on Landsat OLI/ETM image (http://www.gscloud.cn) and Google Earth image data (https://earth.google.com). 2) The socio-economic data were obtained from the Statistical Yearbook and the Statistical Bulletin of Jiangjin District.

Author contributions

CZ: Writing- Reviewing and Editing. HT: Writing-Reviewing and Editing. MZ: Supervision and Data collection. ZW: Methodology.

Funding

This work was supported by the general project of Chongqing Social Science Planning “Research on Sustainable Development of Livelihood of Poverty-alleviation Households Driven by New Rural Communities and Rural Tourism” (Grant No. 2022NDYB80).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 12 December 2022
DOI 10.3389/fenvs.2022.1067339

Does China's poverty alleviation policy improve the quality of the ecological environment in poverty-stricken areas?

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SPECIALTY SECTION
This article was submitted to Environmental Economics and Management, a section of the journal Frontiers in Environmental Science

RECEIVED 11 October 2022
ACCEPTED 02 December 2022
PUBLISHED 12 December 2022

CITATION
Ran R, Ni Z, Hua L and Li T (2022), Does China's poverty alleviation policy improve the quality of the ecological environment in poverty-stricken areas? *Front. Environ. Sci.* 10:1067339.
doi: 10.3389/fenvs.2022.1067339

Poverty eradication and environmental protection as the two global goals of sustainable development. China's poverty alleviation policy attempts to achieve green development in poverty-stricken areas by eliminating poverty while also promoting environmental protection. Since the Poverty-stricken counties on the Qinghai-Tibet Plateau also have the dual attributes of ecological degradation and ecological fragility, it is of great significance to study the impact of poverty alleviation policy on their environment. In this research, taking poverty alleviation policy as the entry point, based on panel data and Remote Sensing Ecological Index for poverty-stricken counties on the Qinghai-Tibet Plateau from 2011 to 2019, and using the difference-in-differences (DID) method to verify the impact of policy on environmental quality. The main findings of the study were: 1) The poverty alleviation policy has a significant improvement effect on the ecological environment quality of counties in the Qinghai-Tibet Plateau region, and this conclusion still holds in a series of robustness tests using methods including the changing sample size method and the variable replacement method. Moreover, the policy effect has a certain time lag and its effect persists in the long term; 2) It is mainly due to the increased level of government public expenditure and the easing of government financial pressure that has contributed to the improvement of environmental quality in poverty-stricken areas; 3) Policy heterogeneity suggests that industrial poverty eradication policies are more conducive to promoting synergistic economic and environmental development in poverty-stricken areas.

KEYWORDS

Qinghai-Tibet plateau, poverty-stricken counties, remote sensing ecological index, poverty alleviation, difference-in-difference (DID) method

1 Introduction

The Chinese government implemented the poverty alleviation policy in 2015, which attempts to completely eliminate absolute poverty in the Chinese region. In 2020, China achieved the total alleviation of poverty in rural areas under the current standard and the removal of all poverty-stricken counties. The average annual number of poverty reduction in the past 5 years is more than 11 million, and regional overall poverty has been solved (Zhu et al., 2014). However, existing studies show that poverty reduction and economic development also bring rapid consumption of resources and environmental damage (Mafi-Gholami and Baharlouii, 2019; Liu et al., 2021), and Poverty-stricken counties overlap highly with ecologically fragile areas geographically and spatially (Wu and Jin, 2020; Wu et al., 2021), which are more likely to cause serious environmental quality deterioration problems in the process of poverty alleviation. At the same time, the policy of poverty alleviation requires ecological poverty alleviation, so it is of great significance to study the impact of poverty alleviation policy on the environment in poor areas to achieve sustainable development.

Environmental quality, a key component of the wellbeing of the world's poor, is deteriorating at an alarming rate (Assessment, 2005). In the current research on poverty governance, scholars generally agree that the "environmental poverty trap" is a major constraint on economic development and environmental protection in poverty-stricken areas (Haider et al., 2018; Zhen et al., 2014). The main reason is that people in poverty-stricken areas are usually located in fragile environments (Zhen et al., 2014), and they are highly dependent on natural resources as a source of economic income and tend to overuse land, forests and other natural resources, causing damage to the ecological environment (Cavendish, 2000; Samal et al., 2003), which in turn may lead to "ecological poverty" (Dasgupta et al., 2005; Guo and Liu, 2021), i.e., in the absence of natural resources and ecological degradation, people are unable to obtain the natural resources they need to sustain their living activities, thus further increasing poverty and creating a vicious spiral. In this vicious cycle, poverty leads to environmental degradation, and environmental degradation further exacerbates poverty (Gupta and Vegelin, 2016; Zhou et al., 2019). At the same time, since poverty governance has been a hot issue of international concern, many countries have implemented a series of policies to try to eliminate poverty. For example, Bangladesh has implemented the Employment Poverty Alleviation Program (Ravallion, 1990); Nigeria has implemented the National Economic Empowerment and Development Strategy (Pereira, 2008). However, these policies only focus on economic benefits and neglect environmental protection, which will easily lead to "resource plundering poverty alleviation" (Comim et al., 2009; Skutsch et al., 2017). Many governments in poor areas will seek economic development at the expense of destroying the environment (Gray and Moseley, 2005), i.e., emphasizing economic benefits at the expense of ecological benefits, short-term benefits at the expense of long-term benefits, accelerating and intensifying the plundering and exploitation of natural resources, which will lead to the deterioration of the environment in their areas. In general, academics generally agree that there is a vicious cycle of poverty and ecological degradation (Cavendish, 2000; Dasgupta et al., 2005; Liu et al., 2008).

Since the 21st century, poverty and the environment have received increasing attention in developing countries as two key elements of sustainable development strategies (Zhen et al., 2014), and there is a large degree of international consensus that environmental protection should be part of all poverty eradication policies and that poverty alleviation and ecological conservation must develop in tandem (Qin and Zhang, 2022; Wiedmann and Allen, 2021; Zhu et al., 2020). Therefore, for the study of current poverty alleviation policies, we should not only focus on the economic effects of poverty alleviation, but also on multi-dimensional improvements (Huang et al., 2022; Zhen et al., 2014). A growing number of scholars believe that pro-poor policies should take into account their environmental effects and give due consideration to the elimination of multidimensional poverty as a way to promote sustainable development strategies (Davies et al., 2014). Therefore, it is now necessary to analyze the impact of economic growth brought about by poverty alleviation on the quality of ecological environment, and to consider its ecological improvement benefits when studying the economic effects of poverty alleviation (Fu et al., 2021). In the current context, quantifying the conflict between poverty alleviation and ecological protection is nothing less than an emerging area of concern (Li R. Q et al., 2021). Unlike the poverty eradication policies implemented in other countries, China's poverty eradication policy emphasizes the relationship between ecological environmental protection and socioeconomic development in the process of poverty eradication, and further clarifies the principles of poverty alleviation policies, requiring ecological protection as the main focus, not at the expense of ecology, and exploring new ways of ecological poverty alleviation to develop the economy and get rid of poverty (Huang, 2022). Although China has successfully established a developmental approach to poverty alleviation with Chinese characteristics and achieved total poverty eradication, the impact of this policy on the ecological environment in poor areas has been generally overlooked (Zhang and Feng, 2020).

Known as the "roof of the world" and the "third pole of the Earth", the Qinghai-Tibet Plateau is a "sensor" and "sensitive area for climate change in Asia and even the Northern Hemisphere (Wang et al., 2016; Wu et al., 2014). The Qinghai-Tibet Plateau is different from other regions of the world because of its high altitude, complex landscape and fragile ecology (Cao et al., 2015). At the same time, as the "water tower of Asia", the ecological protection of the Qinghai-Tibet Plateau is of great importance, not only for the sustainable development of the whole East Asia region, but also for the environmental changes that will indirectly affect other regions of the world (Dong et al., 2020; Mahmood et al., 2020; Wang et al., 2015). Therefore, ecological changes on the Qinghai-Tibet Plateau have been one of the hot spots for global environmental and sustainable development research (Jiang et al., 2017). According to the national-level poverty counties

TABLE 1 Descriptive statistics of the main variables.

Variable name	Variable definition	Average value	Standard deviation	Minimum value	Maximum value
RSEI_Index	Ln (RSEI*100 + 1)	3.902	0.282	2.511	4.410
Treat·T		0.497	0.500	0	1
ID	The ratio of the number of industrial enterprises above the scaleto the area of the jurisdiction*10	0.0555	0.421	0	8.696
second	The ratio of gross value of secondary industry (million yuan) to gross regional product (million yuan)	0.290	0.193	0.00522	0.921
NDVI	Normalized Difference Vegetation Index	0.719	0.116	0.323	0.864
pd	The ratio of total population to jurisdictional area at the end of year for each county	0.0286	0.176	0.0000086	3.545
lnPGDP	The logarithm of GDP *per capita*	9.805	0.692	7.931	12.94
Third	The ratio of gross tertiary sector product (million yuan) to gross regional product (million yuan)	0.41	0.162	0.02	0.960
EPI	GDP annual growth rate	0.154	0.413	-0.872	7.977
GFP	Local government fiscal vertical imbalance rate	0.49	2.53	0.007	26.438
GPS	Logarithm of local government fiscal expenditures	11.395	0.87	7.2	13.271

data released by the Chinese government, it can be found that the regional poverty rate in the Qinghai-Tibet Plateau region is high, and its regional GDP only accounts for 0.64% of China's GDP (Qi and Li, 2021; Qi et al., 2022), and the poverty-stricken counties on the Qinghai-Tibet Plateau suffer from backward productivity, single industrial structure, and inefficient resource development, which greatly limit their economic development. On the other hand, the poverty-stricken counties on the Qinghai-Tibet Plateau overlap geographically and spatially with the "Protection Plan for China's Ecologically Fragile Areas" issued by the Chinese Ministry of Environmental Protection. Therefore, the poverty-stricken counties on the Qinghai-Tibet Plateau have multiple characteristics such as ecological fragility, ecological degradation, high incidence of poverty, and backward productivity, which are more special and representative than other poor regions (Qi et al., 2022; Wang et al., 2020), and it is easier to identify the environmental impacts caused by the economic development and human production and life carried out during the implementation of the poverty alleviation policy, which provides a good research sample for the study of this paper, so this paper chooses the poverty-stricken counties on the Qinghai-Tibet Plateau as the research object.

In summary, scholars have now begun to approach policies related to poverty eradication from several aspects and dimensions (Hou et al., 2021; Howe et al., 2013; Huang et al., 2022; Rakatama and Pandit, 2020). However, there are fewer studies on the impact of poverty eradication on the environment (Fu et al., 2021), and few papers quantify the policy effects of poverty alleviation policies on environmental protection from the perspective of policy evaluation (Li T et al., 2021; Malerba, 2020), so it is impossible to make a scientific and accurate evaluation of the policy effects, and the conclusions drawn from the existing literature through correlation analysis are not sufficient to truly reflect the law of causality. In view of this, this paper considers poverty alleviation policy as a "quasi-natural experiment" and takes the Qinghai-Tibet Plateau region, where poverty and ecological degradation coexist, as a sample to evaluate the ecological conservation effect of poverty alleviation policy using the difference-in-differences model, which provides a reference for the design of green poverty alleviation policy. In particular, based on a systematic and rigorous empirical study, this paper attempts to explore the following central but not yet well answered questions: Does poverty alleviation policy help improve the ecological and environmental quality of counties in the Tibetan Plateau region? What is the mechanism of its impact on environmental quality? In order to provide a basis and reference for eliminating relative poverty and achieving common prosperity in poor areas, and to provide policy reference for poverty alleviation undertakings and ecological governance in other poor countries.

Compared with the existing research results, the contributions of this paper are reflected in the following four aspects: 1) Starting from the environmental effects of policy, we examine the effects and transmission mechanisms of poverty alleviation policy, and identify the policy effects by using the difference-in-differences model, which makes up for the lack of research on the environmental effects of poverty alleviation policy in current studies. 2) Discuss the environmental effects of different kinds of policy in terms of heterogeneity, and provide proven policy recommendations for further improving the

TABLE 2 Baseline return.

Variable name	Environmental quality level							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Treat·T	0.407***	0.445***	0.223***	0.209***	0.152*	0.152*	0.193**	0.195**
	(4.65)	(4.85)	(3.38)	(3.20)	(1.96)	(1.96)	(2.21)	(2.22)
Third		0.204**	0.275***	0.253***	0.554***	0.544***	0.496***	0.496***
		(2.11)	(3.52)	(3.38)	(6.77)	(6.73)	(6.61)	(6.59)
lnPGDP			−0.205***	−0.211***	−0.261***	−0.263***	−0.269***	−0.270***
			(−6.64)	(−6.88)	(−7.78)	(−7.65)	(−7.72)	(−7.67)
EPI				0.045***	0.050***	0.051***	0.058***	0.058***
				(3.72)	(3.76)	(3.70)	(4.02)	(4.02)
second					0.380***	0.383***	0.418***	0.419***
					(4.72)	(4.71)	(4.99)	(5.00)
ID						0.161	−2.526*	−2.513*
						(0.84)	(−1.79)	(−1.78)
pd							0.703**	0.699*
							(1.97)	(1.96)
NDVI								0.038
								(0.50)
Constant term	4.082***	4.004***	5.883***	5.941***	6.190***	6.212***	6.275***	6.260***
	(137.68)	(80.44)	(22.04)	(22.54)	(21.88)	(21.34)	(21.22)	(21.41)
Regional fixed effects	YES	YES	YES	YES	YES	YES	YES	YES
Time fixed effects	YES	YES	YES	YES	YES	YES	YES	YES
N	513	513	513	513	513	513	513	513
R^2	0.420	0.431	0.593	0.597	0.627	0.627	0.636	0.636

Note: *, ** and *** denote 10%, 5% and 1% significant levels, respectively; t-statistics are in parentheses.

poverty alleviation strategy and achieving the dual goals of poverty alleviation and ecological improvement. 3) For the assessment of policy effects, some existing empirical studies in the literature use the single-difference method to assess policy effects by comparing the differences in economic performance before and after poverty alleviation measures, and this simple comparison method cannot identify the net growth effects of poverty alleviation policy after excluding other influencing factors (Wu et al., 2021; Zhang et al., 2022), so this paper overcomes the estimation bias in some previous studies by using the difference-in-differences model to identify the poverty alleviation the net effect of poverty alleviation policy on environmental improvement, and applying multiple methods to robustness test the results. 4)Most of the existing studies carry out econometric analysis in terms of provinces and municipalities, and there is little literature on the effects of poverty alleviation policy on the ecological environment quality in ecologically fragile and poor areas. Current research generally agrees that environmental protection and poverty eradication are incompatible, that economic development in poor areas leads to environmental degradation, and that whether efforts to reduce poverty reduce or exacerbate environmental degradation remains a long-standing debate in the economics literature. This paper measures the environmental effects of China's poverty eradication policies through an empirical study, and the results show that China's poverty alleviation policy that requires synergistic development of economic development and environmental protection can achieve compatibility between environmental protection and economic development in poor areas, which makes certain

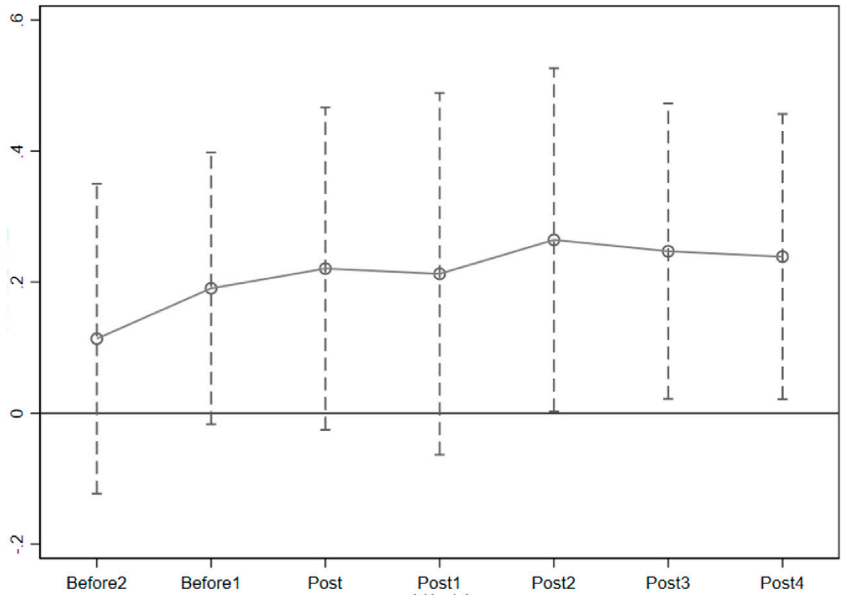

FIGURE 1
Parallel trend test.

additions to the relevant studies of poverty trap theory and provides suggestions for the formulation of poverty alleviation policies in other countries. This paper investigates the development of Poverty-stricken counties on the Qinghai-Tibet Plateau in China in the context of poverty alleviation policy.

2 Literature review and research hypotheses

2.1 Literature Review

The current evaluation of poverty alleviation policy mainly focuses on one dimension of their policy, and most studies only focus on the relationship between support policy and economic aggregates, that is, on the growth effect of policy or the quantitative effect of policy, while some scholars also study the industrial structure upgrading effect, fixed investment effect, employment effect, and sustainable development capacity effect of policy (Busso et al., 2013; Cristina and Guido, 2011; Giua, 2017). For example, Park evaluated the economic growth effect of large-scale poverty alleviation program on counties and found that the implementation of the policy significantly promoted the economic development of counties (Park et al., 2002); Some scholars have also evaluated the economic effect of the establishment of poverty eradication policies and used the PSM-DID model to study the effect of the implementation of poverty eradication policies on local economic development, and empirically found that the implementation of poverty eradication policies has a significant and sustained promotion effect on local economic development, and the longer the poverty eradication policies are implemented, the greater the promotion effect (Deng et al., 2022; Jiang et al., 2021; Yang et al., 2022).

However, a growing number of scholars believe that poverty-stricken policies should take into account environmental effects and give due consideration to the elimination of multidimensional poverty as a way to promote sustainable development strategies (Brooks et al., 2012; Leffel et al., 2022; Porras and Asquith, 2018). For example, Barbier argues that emissions reduction policy may affect economic development for poverty reduction and that there is a need to assess how the design and implementation of emissions reduction policy affect the potential trade-offs between positive and negative impacts on poverty reduction and to study emissions reduction and poverty reduction together (Barbier, 2014); Howe argues that there are complex interlinkages between ecology and poverty and that it is important to develop policy in these areas recognize the importance of these linkages and study them together (Howe et al., 2013); Meijaard argues that previous studies have focused on the environmental outcomes of policy and ignored their economic consequences, and that there is now a need to focus on the impact of policy on both poverty reduction and environmental protection outcomes (Meijaard et al., 2020); Brashares argues that poverty is a key constraint on environmental protection, that poverty must be addressed to achieve environmental protection goals, and that environmental

TABLE 3 Robustness tests.

Variable name	Change time interval			Replacing variable measurements	Using the tobit model	Truncation processing	Change model settings	Propensity score matching	Lagged core explanatory variables
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Treat·T	0.221*	0.232**	0.202**	0.118***	0.027***	0.326***	0.190**	0.606**	0.261***
	(1.88)	(1.98)	(2.18)	(3.87)	(2.96)	(2.95)	(2.08)	(2.53)	(2.79)
Third	−0.174	−0.103	−0.013	0.156**	0.028	0.602***	0.507***	0.555***	0.440***
	(-1.22)	(−0.92)	(−0.14)	(2.31)	(0.76)	(6.20)	(6.35)	(4.56)	(5.25)
lnPGDP	−0.226***	−0.218***	−0.250***	0.001	−0.067***	−0.269***	−0.259***	−0.272***	−0.291***
	(−3.60)	(−4.65)	(−6.15)	(0.07)	(−8.60)	(−6.93)	(−6.89)	(−4.33)	(−6.95)
EPI	0.091***	0.079***	0.082***	−0.013	0.025**	−0.107	0.055***	0.081***	0.073***
	(3.06)	(2.66)	(2.87)	(−1.12)	(2.32)	(−0.75)	(4.26)	(2.75)	(3.97)
second	0.175	0.148	0.232**	0.104*	0.078**	0.584***	0.406***	0.781***	0.489***
	(1.06)	(1.30)	(2.19)	(1.69)	(2.45)	(7.14)	(4.48)	(7.40)	(5.04)
ID	−0.544	−1.678	−1.828*	2.960***	−0.483	−21.910**	−2.189	−17.726**	−2.070*
	(−0.55)	(−1.47)	(−1.78)	(3.89)	(−1.09)	(−2.59)	(−1.55)	(−2.36)	(−1.74)
pd	1.122**	1.461***	1.394***	−0.882***	0.144	2.029***	0.600*	12.217	1.158***
	(2.30)	(3.23)	(3.69)	(−4.57)	(1.29)	(3.38)	(1.68)	(1.21)	(2.98)
NDVI	−0.467***	−0.296***	−0.029	0.300***	−0.275***	−0.036	0.039	−0.147**	0.012
	(−3.91)	(−3.04)	(−0.28)	(4.07)	(−6.94)	(−0.48)	(0.48)	(−2.12)	(0.16)
var(e.mean)					0.010***				
					(16.02)				
Constant term	6.436***	6.267***	6.343***	4.173***	1.302***	4.726***	6.159***	6.249***	6.501***
	(11.26)	(14.66)	(17.36)	(32.09)	(18.42)	(29.57)	(19.65)	(11.56)	(18.23)
Regional fixed effects	YES	YES	YES	YES	YES	YES	YES	YES	YES
Time fixed effects	YES	YES	YES	YES	YES	YES	YES	YES	YES
N	171	285	399	513	513	513	456	211	456
R^2	0.427	0.410	0.444	0.479		0.572	0.634	0.766	0.647

Note: *, ** and *** indicate 10%, 5% and 1% significant levels, respectively; t-statistics in parentheses.

protection activities must not undermine poverty reduction, so that environment and poverty need to be studied in a unified framework (Brashares et al., 2004); Huang argues that scholars should not only focus on the poverty alleviation effects of policy, but also on the multidimensional improvement effects of policy, and that the assessment of policy should be comprehensive (F. B. Huang et al., 2022); Hayes et al. (2015) argues that in the process of horizontal ecological compensation policy implementation, the implementation objectives should gradually change from the initial single objective (improving the ecological environment) to multiple objectives (ecological environment and economic development); Chen argues that the current design of the policy needs to focus on both the environment and the economy, and breaking the dilemma of economic growth and environmental quality improvement is an urgent problem to be solved at present (Chen et al., 2021).

Therefore, with the gradual advancement of practical and theoretical understanding, scholars began to incorporate both ecological and environmental governance and poverty reduction into the research framework of policy (Alix-Garcia et al., 2013;

TABLE 4 Mechanisms of the impact of poverty alleviation policy on RSEI_Indexit.

Variable name	Public expenditure level				Government financial pressure			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	GPS_{it}	GPS_{it}	$RSEI\_Index_{it}$	$RSEI\_Index_{it}$	GFP_{it}	GFP_{it}	$RSEI\_Index_{it}$	$RSEI\_Index_{it}$
Treat·T	0.594**	0.641**	0.327***	0.128**	−2.417*	−2.101*	0.278***	0.104*
	(2.27)	(2.31)	(6.18)	(2.12)	(−1.88)	(−1.72)	(6.21)	(1.71)
GPS			0.135***	0.104***				
			(4.43)	(5.30)				
GFP							−0.053***	−0.043***
							(−6.01)	(−5.39)
Controls	NO	YES	NO	YES	NO	YES	NO	YES
Constantterm	10.771***	13.459***	2.628***	4.864***	0.430*	−15.478***	4.107***	5.592***
	(85.50)	(16.73)	(7.77)	(17.06)	(1.86)	(-3.52)	(173.31)	(26.24)
Regional fixed effects	YES	YES	YES	YES	YES	YES	YES	YES
Time fixed effects	YES	YES	YES	YES	YES	YES	YES	YES
N	513	513	513	513	511	511	511	511
R^2	0.318	0.383	0.539	0.699	0.068	0.383	0.630	0.727

Note: *, ** and *** indicate 10%, 5% and 1% significant levels, respectively; t-statistics in parentheses.

Barbier, 2014)and began to study the environmental effects of poverty alleviation policy and the poverty reduction effects of environmental policy, for example, Huang studied whether photovoltaic poverty alleviation achieved low carbon development while achieving poverty reduction (F. B. Huang et al., 2022); Meijaard studied whether community forestry policy were local economic downturns when they achieved forest conservation outcomes (Meijaard et al., 2020); Jennifer used discontinuities in community-level eligibility rules for conditional cash transfer projects in Mexico and stochastic changes in the pilot phase of the project to study the impact of poverty-stricken projects on environmental degradation (Jennifer et al., 2013); Zhou studied whether the implementation of action plan of air pollution prevention and control was again at the expense of economic growth (Zhou and Tang, 2021).

It is clear from the above analysis that scholars have mostly focused on the economic effects of poverty alleviation policy, and a few have begun to discuss how to achieve sustainable development while eradicating poverty, however, the environmental effects of poverty alleviation policy have not been effectively measured. We discuss the effects of China's poverty alleviation policy on local environmental quality.

2.2 Theoretical mechanisms

First, the implementation of poverty alleviation policy will have a direct impact on the quality of ecological environment. The impact of current policy with environmental regulation effect on ecological and environmental quality mainly has two views: "push-back effect" and "regressive effect". The "regressive effect" refers to the government's efforts to increase production costs and restrain the production behavior of enterprises (especially those with high pollution and energy consumption) through mandatory orders and setting energy conservation and emission reduction targets, and to force enterprises to carry out green technological innovation and improve management models to reduce carbon emissions (Fuenfgelt and Schulze, 2016; Zhu et al., 2014). Both the "green paradox" and "bottom-up competition" will lead to a decline in environmental quality after the implementation of policy with environmental regulatory effects, i.e., the "regressive effect" (Blackman and Kidegaard, 2003; Gray and Shadbegian, 2003). The "green paradox" is that when the government introduces environmental policy to improve the environment, there is a sudden increase in the consumption of fossil energy, leading to environmental degradation (Sinn, 2008). The pursuit of economic benefits by local governments leads to the "bottom-up effect" of environmental regulations, resulting in the deterioration of local environmental quality (Ouyang et al., 2020; Ghanem and Zhang, 2014). In fact, with the increasingly prominent contradiction between economic development and environmental protection, the evaluation mechanism of government officials based on GDP assessment is being reversed, and environmental performance is gradually becoming an important element of officials' performance assessment (Jia et al., 2014; Piotroski and Zhang, 2014), therefore, according to the promotion tournament theory, the policy of poverty alleviation will also certainly influence the governance behavior of local officials, which in turn will have an impact on local economic and social development. Therefore, the current impact of environmental regulation on regional ecological environment is mainly manifested as a push back effect (Huang, 2022). For the sustainable development of poor regions, the poverty alleviation policy has strengthened regional environmental regulation by quantifying factors such as changes in ecological environment and increasing environmental expenditure. Therefore, the following hypothesis is proposed in this paper.

Hypothesis 1: The poverty alleviation policy can significantly improve the ecological quality of counties on the Qinghai-Tibet Plateau.

Second, poverty alleviation policy may improve the level of ecological quality by raising the level of public expenditure and relieving government fiscal pressure. First, the policy of poverty alleviation can enhance the level of public expenditure of county governments, thus realizing the improvement of local ecological and environmental quality. Fiscal expenditure, as an important component of environmental finance, is closely related to environmental pollution (Shao et al., 2022; Zahra et al., 2022), and the level of fiscal expenditure largely influences the differentiation of provincial economic quality development (Wang et al., 2022), and increased government public expenditure tends to significantly improve the level of local ecological and environmental quality (Lin and Zhou, 2021a; Zhu et al., 2022), and some scholars even directly argue that the proportion of government expenditure to GDP is positively related to the level of air pollution (Carlsson and Gable, 2000; López et al., 2011). On the other hand, fiscal expenditure, as a mechanism factor, has a positive impact on the stability of industrial ecosystems (Guild, 2020; Schmidt et al., 2014; Zhu et al., 2022), and existing studies found that there is a significant spatial auto correlation between local fiscal expenditure and the level of industrial ecology, and the government can promote the stable development of local industrial ecosystems by guiding social funds through public expenditure (Guild, 2020; Schmidt et al., 2014), which is conducive to promoting the improvement of the local environment. And the implementation of the policy of poverty alleviation will make the local government pay more attention to the assessment from the higher level, thus changing the investment in environmental management and increasing public expenditure according to the importance of the assessment index from the higher level (Westmore, 2018; Zeng et al., 2021), so this will help the local improvement of the environmental quality condition. Secondly, the poverty alleviation policy can relieve the financial pressure of county governments and enhance the willingness and enthusiasm of local governments to protect the environment, thus improving the level of ecological and environmental quality. The Qinghai-Tibet Plateau region is constrained by the low level of economic development, the lack of own and external funds, and the high financial pressure, the poverty alleviation policy can alleviate the hindering effect of the local government to carry out environmental protection. From the dimension of financial resources, the implementation of environmental policy in different places usually depends on central financial incentives and local financial capacity (Dunlop and Corbera, 2016; Qi and Zhang, 2014), and sufficient financial resources are an important guarantee for local governments to implement environmental governance (He et al., 2012; Tacconi et al., 2008), while when there is a large financial pressure, it changes local government behavior, making local governments pay more attention to economic growth and neglect the environment, and this incentive effect formed by financial pressure is This incentive effect formed by fiscal pressure is an important reason for the growth of industrial pollution in China (Hui et al., 2022). In contrast, the implementation of the poverty alleviation policy has led the state to increase the intensity of investment in poverty alleviation funds in counties (Luo et al., 2021), and the financial transfer payments shared at the central, provincial, counties, and county levels have reconciled the contradictions between the central and local governments in terms of financial resources (financial power) and environmental governance matters (affairs) (Gong et al., 2020), bringing an increase in the level of financial security of local governments (Su et al., 2021; Wen and Lee, 2020), which has helped to alleviate the financial pressure on local contributes to the improvement of urban productivity and resource use efficiency (Hou et al., 2022; Hui et al., 2022), significantly increases the willingness and motivation of local governments to protect the environment (Zhang and Zhao, 2018), and therefore this will help localities to improve the environmental quality situation. Accordingly, this paper proposes hypotheses two and three:

Hypothesis 2: Due to the change in the level of government public expenditure, the poverty alleviation policy will affect the level of local environmental governance. According to the above discussion, the "poverty alleviation policy" will be beneficial to environmental governance, i.e., it will positively affect the remote sensing ecological index.

Hypothesis 3: Due to the change of government financial pressure, the poverty alleviation policy will affect the level of local environmental governance. According to the above discussion, the "poverty alleviation policy" will benefit environmental governance, i.e., positively affect the remote ecological index.

3 Study design and data description

3.1 Empirical model construction

The question explored in this paper is whether the implementation of poverty alleviation policies has been

TABLE 5 Mechanistic test of government financial pressure.

Variable name	Small administrative area	Large administrative area	Low altitude	High altitude	Low industry advanced	High industrial sophistication	Industrial poverty alleviation	Ecological compensation
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Treat·T	0.171**	0.086*	0.188**	0.053	−0.038	0.340***	0.222***	0.194***
	(2.27)	(1.94)	(2.26)	(1.27)	(−0.87)	(3.45)	(2.62)	(2.94)
Third	0.364***	0.387***	0.381***	0.428***	−0.176	1.844***	0.381***	1.390***
	(3.29)	(4.36)	(3.43)	(4.73)	(-1.44)	(4.74)	(5.39)	(6.75)
lnPGDP	−0.288***	−0.149***	−0.290***	−0.124***	−0.268***	−0.406***	−0.244***	−0.378***
	(−7.38)	(−5.12)	(−6.48)	(−4.60)	(−3.95)	(−7.24)	(−6.69)	(−5.47)
EPI	0.066***	0.032	0.071***	0.034	−0.046	0.065***	0.058***	0.052**
	(4.57)	(1.01)	(4.92)	(0.98)	(−0.50)	(4.69)	(4.19)	(2.11)
second	0.107	0.549***	0.247*	0.581***	0.506***	1.488***	0.242***	1.433***
	(0.85)	(6.07)	(1.92)	(6.09)	(5.35)	(4.10)	(3.10)	(7.90)
ID	−1.753	−6.831	−2.167*	33.966	−0.889	−6.755***	−2.100	5.518
	(−1.59)	(−0.60)	(−1.74)	(1.45)	(−0.73)	(−3.17)	(−1.58)	(0.26)
pd	0.519*	206.124***	0.630*	147.107***	0.972	1.665***	0.581*	188.133***
	(1.82)	(5.88)	(1.96)	(7.32)	(1.44)	(3.17)	(1.71)	(7.70)
NDVI	−0.174	0.128*	0.106	−0.040	−0.019	−0.204	0.056	0.542**
	(−1.34)	(1.84)	(0.62)	(−0.84)	(−0.30)	(−1.56)	(0.63)	(2.19)
Constant term	6.693***	4.982***	6.493***	4.882***	6.537***	6.764***	6.082***	5.764***
	(19.83)	(19.98)	(17.74)	(21.01)	(10.24)	(18.66)	(19.64)	(11.86)
Regional fixed effects	YES	YES	YES	YES	YES	YES	YES	YES
Time fixed effects	YES	YES	YES	YES	YES	YES	YES	YES
N	251	262	261	252	256	257	342	171
R^2	0.737	0.710	0.706	0.670	0.700	0.745	0.658	0.658

Note: *, ** and *** indicate 10%, 5% and 1% significant levels, respectively; t-statistics in parentheses.

10.3389/fenvs.2022.1067339

effective in improving the environment of poverty-stricken counties on the Qinghai-Tibetan plateau region. Since areas with better ecological endowments coincide with poorer areas, in order to accurately estimate the causal effect of poverty eradication policy implementation on county ecological quality, it is necessary to exclude endogeneity due to omitted variables, reverse causality and interference from other factors, and reduce the interference of endogeneity in the identification of disturbance causality. Therefore, this paper adopts the difference-in-differences (DID) model (Alari et al., 2021; Wang and Li, 2019) and refers to the model settings of Chen and Xu, on the basis of controlling for regional and year fixed effects (Chen et al., 2020; Xu et al., 2021), eliminating the differences in natural, geographic and economic conditions that do not change over time between the two groups before and after the policy intervention and external shocks from the national level (Athey and Imbens, 2006; Davies et al., 2008; Hawkins and Baum, 2016), in order to exclude other factors from interfering as much as possible, and finally obtain the following model 1). For robustness testing, this paper uses a series of methods such as propensity score matching method, changing time intervals, changing variable measures, changing model settings, and lagging variables to test the robustness of the results.

$$RSEI\_Index_{it} = \beta_0 + \beta_1 Treat \cdot T + \beta_2 control_{ir} + \eta_t + \mu_i + \varepsilon_{it} \quad (1)$$

where the subscript i represents the county and t represents the time. $RSEI\_Index_{it}$ is the explanatory variable measuring the environmental quality of the county, and the subscripts i and t represent the *ith* county and the year. *Treat* is used to distinguish the treatment group from the control group, T is used to distinguish before and after the policy implementation, and the cross product term $Treat{\cdot}T$ is the core explanatory variable in this paper. $Treat{\cdot}T = 1$ if it occurs after the policy and the county is a poverty-stricken county, that is, out of poverty in 2019, otherwise $Treat{\cdot}T = 0$. Control represents a series of control variables. η_t controls for time-level characteristics that do not vary with region, such as changes in macroeconomic situation;μ_i controls for region-level characteristics that do not vary with time; and ε_{it} denotes a random disturbance term. The coefficient β_1 indicates the impact of the poverty alleviation policy on the ecological environment quality of poverty-stricken counties, and is the core parameter of interest in this paper.

3.2 Data settings

Explained variable: The environmental quality level *RSEI_Index* is the explanatory variable, and the logarithmic value of Remote Sensing Ecological Index (RSEI) (*ln(RSEIit*100+1)*) of each county in the Qinghai-Tibet Plateau region is selected to measure the environmental quality level of counties in the Qinghai-Tibet Plateau region. The remote sensing ecological index data were obtained from the National Earth System Science Data Center of China by projection conversion, resampling and cropping.

Core explanatory variables: The cross-product term $Treat{\cdot}T$ is the core explanatory variable, representing whether the poverty-stricken counties implement the poverty alleviation policy. Among them, *Treat* is the policy dummy variable, which is assigned as 1 if the sample county is a national-level poverty-stricken county in the Qinghai-Tibet Plateau region that will be out of poverty in 2019, and 0 otherwise; T is the experimental period dummy variable, which is assigned as 1 after 2015 (including 2015) and 0 before 2015. The coefficient estimate β_1 of the cross-product term $Treat{\cdot}T$ is the DID estimator, which represents the net impact of the policy on county environmental quality, $Treat{\cdot}T$ is assigned a value of 1 when and only when the i_{th} county is a national-level poverty-stricken county in the Qinghai-Tibet Plateau region that escapes poverty in 2019 and $t \geq 2015$, and 0 otherwise.

Control variables: Regional environmental quality levels are influenced by a variety of factors, and drawing on relevant research practices, the following variables are controlled for in this paper.1) Per capita income level (*lnPGDP*): economic growth and other factors have caused an increase in carbon dioxide emissions, which has put great pressure on environmental quality (Liu et al., 2020). Academics usually use gross domestic product (*GDP*), gross national product (*GNP*), and *per capita* income level to measure the economic status of a country or region, while *per capita* regional GDP is more representative of economic growth than, for example, regional GDP (Dedecek and Dudzich, 2022; Guio et al., 2015). Therefore, in this paper, the logarithm of the *per capita* regional GDP (yuan) of each county is used to indicate the level of *per capita* income. 2) Share of tertiary industries (*Third*). The ratio of gross value of tertiary industry (million yuan) to gross regional product (million yuan) is used to express this indicator (He et al., 2018). 3) Population density (*pd*): population density is the ratio of the total population of each county at the end of the year to the area of the jurisdiction (Aarstad et al., 2016; Shah et al., 2020), which characterizes the degree of population concentration; the higher the population density, the higher the degree of concentration of enterprises and public service facilities around it, and the more serious air pollution emissions, which is not conducive to pollution control (Frank and Enngelke, 2005; Schweitzer and Zhou, 2010). 4) Economic performance index (*EPI*). It has been suggested that the pursuit of economic performance motivates local governments to devote themselves to areas that can bring promotion, crowding out resource inputs for environmental protection and weakening local environmental control standards, thus undermining the environmental quality of the region (Jiao et al., 2011; X. Wang et al., 2020; Wang and Lei, 2020), so with reference to Zhangchose GDP growth rate as an economic performance indicator (Zhang, 2020). 5)

Industrialization level (*second*): the level of industrialization and environmental quality are interrelated, and the evolution of industrial structure has a significant impact on the ecological and environmental quality in China (Xu et al., 2022), so the ratio of gross secondary industry product (million yuan) to gross regional product (million yuan) was used to represent this indicator (Lin and Zhu, 2019). 6) Enterprise density (*ID*). The spatial concentration of a large number of industrial enterprises leads to an increase in the total amount of industrial pollutants discharged in the region and an increase in the degree of environmental damage (Li H et al., 2020; Panda and Siva Nagendra, 2018), and is therefore measured by the ratio of the number of industrial enterprises above the scale to the area of the jurisdiction (Lin et al., 2022). 7) Vegetation index (*NDVI*): in this paper, the normalized difference vegetation index (NDVI) is used to measure the level of urban greening, which may have both positive and negative effects on air quality; on the one hand, green areas as carbon sinks can play a role in purifying the air, and on the other hand, excessive investment in urban green areas may crowd out environmental protection expenditures in other areas (Yu et al., 2022).

3.3 Data description and descriptive statistic

This paper assesses the policy effects of poverty alleviation policy by using panel data of 57 districts and counties (county-level cities) in the Qinghai-Tibet Plateau region from 2011 to 2019. Considering that Poverty-stricken counties in the Qinghai-Tibet Plateau region were removed from the list of national-level Poverty-stricken counties one after another in 2016–2018, the sample does not include counties that were removed from poverty in 2016–2018. Our principles for selecting the control group include: The control group should not have implemented the poverty alleviation policy and will not be subject to policy intervention, and the trend of ecological environment level of the experimental and control groups before the policy should be the same, i.e., they meet the requirement of parallel trend test. Based on the above principles, we summarized the factors affecting the quality of regional ecological environment based on previous studies, mainly including environmental factors (temperature, precipitation, air pressure, altitude, etc.), geographical factors (topography, vegetation cover, etc.) and socio-economic factors (population density, economic level, industrial structure, etc.) (Ahmed et al., 2019; Cui et al., 2022; De Carvalho and Szlafsztein, 2019; Hua et al., 2020; Liu et al., 2017). Therefore, non-poverty-stricken counties with consistent environmental and geographical conditions should be selected as the control group. If the study expands the scope of sample selection by choosing counties outside the Tibetan Plateau region, it will make the estimation results disturbed by other environmental, socio-economic and policy factors, thus violating our sample selection principle. Therefore, we excluded non-Qinghai-Tibetan Plateau areas and counties with only some areas on the Qinghai-Tibetan Plateau, and selected six counties, including Gulang County and Haixi Mongolian-Tibetan Autonomous Prefecture, as control groups. Therefore, in this paper, the 51 Poverty-stricken counties that successfully escaped from poverty in 2019 are selected as the treatment group, and the sample of districts and counties (county-level cities) in the remaining sample is taken as the control sample, using the national implementation of poverty alleviation policy in 2015 as the external policy shock point. The relevant data were obtained from the China County (City) Social and Economic Statistical Yearbook, the China County Statistical Yearbook, and the district and county statistical bulletins in previous years. Normalized Difference Vegetation Index (NDVI) data were obtained from the 15 days maximum synthetic data published by the Global In-ventor Modeling and Mapping Studies (GIMMS3g) of NASA (https://ecocast.arc.nasa.gov/data/pub/gimms/). The definitions and descriptive statistics of each variable are shown in Table 1.

4 Results and discussion

4.1 Analysis of benchmark model results

Table 2 reports the results of testing the impact of the poverty alleviation policy on the regional environmental quality level using the difference-in-differences method. Model 1) is the baseline model without any control variables, and control variables such as the *Third, lnPGDP, EPI, second, ID, pd,* and *NDVI* are added sequentially from the model (2) to model (8). In the process of adding the control variables in turn, the coefficients of the core explanatory variables *RSEI_Index* always remain significantly positive and the coefficient values do not change significantly, which reflects the robustness of the model estimation results to a certain extent.

In terms of the core explanatory variables that are of most interest in this paper, their regression coefficients are consistently positive at the 1% significance level, indicating that the operation of China's poverty alleviation policy significantly contributes to the improvement of the environment in the Tibetan Plateau region and that China's poverty alleviation policy has exerted the expected policy effect. The regression coefficient of the policy variable in the model (8) is 0.195, indicating that the poverty alleviation policy improves the ecological quality by 19.5%. This result implies that with the poverty alleviation policy, it significantly contributes to the improvement of the environment in the Tibetan Plateau region, allowing the pilot areas to achieve coordinated environmental and economic growth.

In terms of control variables, the regression coefficients of lnPGDP and ID are significantly negative at the 1% level, which is also largely consistent with the findings of previous scholars (Xu et al., 2022; Ward and Shively, 2012): economic and industrial development will be detrimental to the local environment, especially in underdeveloped areas, the negative environmental impact of industrial development is more pronounced, and the higher the density of enterprises will bring about greater pollution. The regression results of other control variables are also basically consistent with the results of previous scholars (Zhou et al., 2013):The rise of secondary and tertiary industries has brought about improvements in the local environment, probably because of the popularity of the Nature Based Solutions (NBS) concept, and more and more companies and industries have started to transform to a sustainable economic development model. Therefore, along with the optimization of the local industrial structure, the economic growth has not caused negative impact on the local environment, and the rise of the economy has also increased the level of local financial resources, which can better protect and improve the environment. EPI has a catalytic effect on the environment, probably because the improved economy has eased the government's financial constraints, which has led to an increase in environmental protection inputs and expenditures and improved environmental quality.

4.2 Parallel trend test

Based on the above methods, we performed coefficient estimation and plotted parallel trends, and the results are shown in Figure 1. It can be seen that in the interval of 2013–2014 years, the estimated coefficients at 90% confidence interval are not significantly different from 0, indicating that there is no significant difference between the ecological and environmental quality levels of the treatment and control groups in the pre-poverty alleviation policy implementation period, which satisfies the parallel trend test; and in terms of dynamic effects, the policy effects in the current period and the first period of policy implementation are not significant, probably because there is a In terms of the dynamic effect, the effect of the policy is not significant in the current period and the first period of policy implementation, probably because there is a time lag in the implementation and execution of the policy, and it takes time to improve the environment, so the environmental improvement effect of the poverty alleviation policy is not significant, while from the second period, the estimated coefficient β_k starts to be significantly different from 0 and lasts until the fourth period, which indicates that the promotion effect of the poverty alleviation policy has a long-term effect and can significantly improve the comprehensive environmental quality level among counties.

4.3 Robustness tests

To further ensure the reliability of the study findings, this paper also performs a series of robustness tests using the DID model of Eq. 1 as the benchmark, the results are shown in Table 3.

4.3.1 Change the time interval

To identify whether the environmental improvement effect of the poverty alleviation policy varies with the length of the sample, this paper identifies the sensitivity of the policy to time changes by varying the regression time interval. This is done by taking the policy occurrence time of 2015 as the middle point, and selecting the samples of 1, 2, and 3 years before and after each regression, if the regression coefficient and significance do not change, it indicates that the estimation results of this paper are robust. The corresponding results are shown in columns (1), (2), and (3) of Table 4. By changing the time interval used for regression, the effect coefficients of the poverty alleviation policy are significantly positive, which still support the previous conclusion, thus proving that the conclusions of this paper are robust.

4.3.2 Replacing variable measurements

The main regression in this paper uses the annual mean value of the remote sensing ecological index as an annual indicator of regional ecological and environmental quality. Compared with the mean value, the public may be more sensitive to the maximum value of the environmental index. Based on this understanding, this paper adopts the annual maximum value of the remote sensing ecological index, which is treated according to the treatment of the explanatory variables in the main regression, as an indicator of the comprehensive ecological and environmental conditions, and the corresponding results are shown in column (4) of Table 4, indicating that the implementation of the poverty alleviation policy has indeed raised the maximum value of the environmental index. Specifically, in terms of the remote sensing ecological index maximum indicator, the implementation of the poverty alleviation policy raised the maximum value of the environmental index by about 11.8%.

4.3.2.1 Using the tobit model

Referring to Xiao, the results were re-tested using the Tobit model considering the Remote Sensing Ecological Index (RSEI) as a restricted variable (Xiao et al., 2021), and the corresponding results are shown in column (5) of Table 3, and the conclusions of this paper are robust.

4.3.2.2 Truncation processing

Robustness test based on sample size. To ensure the robustness of the regression results and to exclude the possible influence of outliers of the variables on the estimation results, the control variables below the 5% and above the 95% quantile are replaced by the 5% and 95% quantile, respectively, and the corresponding results are shown in column (6) of Table 3. The policy of poverty alleviation can significantly improve the level of environmental quality in the county, which proves that the estimation results are robust.

4.3.3 Change model settings

The control variables in model 1) contain regional economic indicators, which may have an inverse effect between them and the implementation of poverty alleviation policy. In order to reduce the potential endogeneity problem, all control variables are lagged by one period and regressed again, and the empirical results are shown in column (7) of Table 3. As can be seen, the sign and significance of the coefficients of the explanatory variables are basically consistent with the results of the benchmark regression, which again verifies the robustness of the conclusions of this paper.

4.3.4 Use propensity score matching (PSM) method

In order to prevent possible sample selection bias and solve the sample self-selection problem, we added the PSM method to further test the results. The PSM method is considered to be a good solution to endogeneity bias (Abadie and Cattaneo, 2018; Dhaliwal et al., 2016; Titus, 2007; Yao et al., 2010), and is therefore widely used in policy evaluation (Mojo et al., 2017; Titus, 2007; Yao et al., 2010). To address the endogeneity issue and more effectively identify the causal relationship between poverty alleviation policy and changes in ecological quality in poverty-stricken counties on the Qinghai-Tibet Plateau, this paper further employs the PSM-DID model to test the robustness of the solution. The rationale for PSM is to make the treatment and control groups "similar" and thus comparable to each other before DID estimation is performed. Therefore, in this paper, the one-to-one nearest neighbor matching method is chosen to match the sample cities to ensure a good consistency of the sample distribution between the treatment and control groups. The final estimation results are shown in column (8) of Table 3, and the findings of the benchmark study in this paper remain robust.

4.3.5 Lags the core explanatory variables

Lagged core explanatory variables are considered to be an effective method that can address endogeneity (Clemens et al., 2012; Green et al., 2005) and are widely used in economics, finance, and other disciplines (Cornett et al., 2007). This method has been adopted by various studies and recognized by many scholars (Cornett et al., 2007; Green et al., 2005). For example, Clemens argues that potential biases in reverse and simultaneous causality can be addressed by lagging core explanatory variables (Clemens et al., 2012), and Buch and Hayo also use this approach in their paper (Buch et al., 2012; Hayo et al., 2010), so this paper refers to existing studies and uses a 1-year lagged core explanatory variable treatment to address endogeneity disturbances. The final estimation results are shown in column (9) of Table 3, and the findings of the benchmark study in this paper remain robust.

4.4 Mechanism of action and pathway analysis

Both the above benchmark regressions and robustness tests indicate that the poverty alleviation policy has a significant improvement on the RSEI of counties in the Qinghai-Tibet Plateau region. In this section, the paper further explores the possible theoretical mechanisms behind this ameliorative effect. As analyzed in Section 2.2, the poverty alleviation policy positively affects the ecological quality of counties in the Qinghai-Tibet Plateau region through two channels: increasing the level of government public expenditure and alleviating government fiscal pressure. To further verify the existence of these effects, we use a two-stage mediated effects model to verify them (Fan et al., 2021).

The first stage is to test the driving effect of the poverty alleviation policy on the two main effects. A mediation model is constructed to test whether the policy variables act on the mediating variable effect is significant, see model 2). If β_1 is not significant, the test of mediating effect is stopped; otherwise, it means that the effect of policy variables on mediating variables is significant and the second stage is entered:

$$GPS_{it}\,(GFP_{it}) = \beta_0 + \beta_1 Treat \cdot T + \beta_2 control_{ir} + \eta_t + \mu_i + \varepsilon_{it} \tag{2}$$

The second stage is to verify the two main effects of the poverty alleviation policy on the RSEI in the Tibetan Plateau region by building an integrated model (3) based on the mediator model (2). If $\beta 2$ is insignificant, there is no mediating effect. Otherwise, there is a mediating effect whether $\beta 1$ is significant or not. If $\beta 1$ is not significant, it indicates that the mediating variable is the only transmission path for the policy variables to have an effect on RSEI in the counties of the Tibetan Plateau region. Otherwise, it indicates the existence of other transmission paths.

$$RSEI\_Index_{it} = \beta_0 + \beta_1 Treat \cdot T + \beta_2 GPS_{it}\,(GFP_{it}) + \beta_3 control_{ir} + \eta_t + \mu_i + \varepsilon_{it} \tag{3}$$

In model (3), *GPSit*, *GFPit* denote two mediating variables. *GPSit* represents the level of government public expenditure, and the logarithm of local government fiscal expenditure is used to measure the level of government public expenditure (GPS) with reference to Sheng's approach (Sheng et al., 2022). *GFPit* stands for Government Fiscal Pressure and, drawing on the practice of Reserve Bank, uses the local government fiscal vertical imbalance rate to measure government fiscal pressure (GFP) (Lin and Zhou., 2021b). The relevant data come from the "China County (City) Social and Economic Statistical Yearbook", "China County Statistical Yearbook" and district and county statistical bulletins in previous years.

The results of the above mechanism tests are shown in Table 4. We first test the mechanism of the level of government public spending. Columns (1) and (2) show that the poverty alleviation policy can significantly increase the level of government public expenditure with or without adding control variables. Columns (3) and (4) test the effect of government public expenditure level on *RSEI_Indexit*.The coefficient of Treat-T is significantly positive and the coefficient of *GPSit* is always significantly positive, indicating that the increase of government public expenditure level can significantly improve the ecological environment quality of counties in Qinghai-Tibet Plateau region, therefore, combining the results of the four columns, we can conclude that:the implementation of the poverty alleviation policy improves the level of government public expenditure and finally enhances the *RSEI_Indexit*.

The remaining four columns test the mechanism of the government's level of financial stress. Columns (5) and (6) show that the poverty alleviation policy significantly alleviates government fiscal pressure with or without the addition of control variables. Columns (7) and (8) test the effect of government fiscal pressure on *RSEI_Indexit*.The coefficient of Treat-T is significantly positive and the coefficient of *GFPit* is always significantly negative, indicating that the alleviation of government financial pressure level can significantly improve the ecological environment quality of counties in the Tibetan Plateau region. Therefore, combining the results in columns (5) to (8), we can conclude that the implementation of the poverty alleviation policy eases the government's fiscal pressure and thus enhances the *RSEI_Indexit*.

4.5 Heterogeneity analysis

Since the heterogeneity of economic base, factor endowment structure, and geographic environment leads to differences in policy effects among different districts and counties, it is necessary to conduct heterogeneity analysis for the baseline regression results. This paper will examine the following three perspectives: (1) whether the policy effect is influenced by the size of the administrative area of the county; (2) whether the policy effect is influenced by the altitude of the county; (3) whether the policy effect is influenced by the level of advanced industrialization in the county; and (4) whether the policy environment improvement effect is influenced by the type of provincial ecological poverty alleviation policy, the results are shown in Table 5.

4.5.1 Administrative area

Since the size of the administrative region affects the difficulty of environmental management in the local counties and the environmental protection expenditure required to be occupied increases, this paper divides the large and small administrative region counties by the mean value of the administrative region of the county, and the results are shown in Table 5. It can be seen that the effect of the poverty alleviation policy on the small administrative region area is more significant and the improvement of the environmental quality of the large administrative region area is less, specifically, the policy on the small administrative regions brought 8.4% higher environmental improvement effect than that for large administrative regions. This may imply that for counties with larger administrative areas, higher-level and local governments need to invest more energy, money, and time in environmental management.

4.5.2 Elevation

Because altitude determines the topographic conditions of a region, high altitude areas are usually mountainous and plateau, which have strong restriction on the scale of local economy and industrial structure, thus the pollution effect of economic development will be higher, and altitude is also an important influencing factor for the diffusion of air pollutants (Jans et al., 2018; Xiao et al., 2021). Therefore, this paper divides high-altitude counties and low-altitude counties according to the mean elevation of the area in which the counties are located, and the results are shown in Table 5, which shows that the poverty alleviation policy can have better environmental enhancement effects in low-altitude areas, while the effects are relatively small in high-altitude areas, which reflects both that the environmental improvement work is more arduous and difficult in high-altitude, and that topographic terrain needs to be considered in regional industrial planning and spatial layout (Q. Li Q et al., 2020; Su et al., 2019).

4.5.3 Advanced industrialization

Both in the near and long term, the optimization and upgrading of industrial structure is important for the effective implementation of environmental policy (Li T et al., 2021). Therefore, in this paper, drawing on Zhou, the industrial structure hierarchy coefficient is used to indicate the industrial structure upgrading, the relative changes in share proportions are used to portray the evolutionary process of the three major industries (Zhou et al., 2020). The specific calculation formula is:

$$AISL_{kt} = y_{i,k,t} \cdot i \quad (4)$$

In Eq. 4, $y_{i,k,t}$ denotes the proportion of the i_{th} industry in the k-county area to the regional GDP in period t. This index reflects the evolution of the three major industries in the Poverty-stricken counties on the Qinghai-Tibet Plateau from the dominant position of the primary industry to the dominant position of the secondary industry and the tertiary industry, so the industrial structure level coefficient is used to measure the industrial structure upgrading, and the average value of the industrial structure level coefficient in counties in previous years is used as the grouping Based on this, the counties are divided into high industrial advanced counties and low industrial advanced counties, and the results are shown in Table 5, which shows that the poverty alleviation policy can have a better environmental upgrading effect in high industrial advanced counties, while the effect is not significant in low industrial advanced counties. This indicates that the degree of industrial structure advanced will affect the effect of the policy on local environmental improvement, so it is necessary to increase the financial investment in regions with backward industrial structure and promote the upgrading of local industrial structure to achieve the purpose of effectively improving the level of environmental quality.

4.5.4 Types of ecological poverty alleviation policy

Based on poverty alleviation policy, local governments have introduced a series of different poverty alleviation policy based on local factors, resource endowments, and other conditions, such as ecological management, industrial poverty alleviation, and ecological compensation, and other related policy. Different ecological poverty alleviation policy will affect the behavior of local governments in environmental protection and will lead to different levels of policy effects, so this paper classifies the types of poverty alleviation into industrial poverty alleviation and ecological compensation based on the content of local poverty alleviation policy based on county and provincial and municipal annual bulletins, and the results are shown in Table 5, which shows that the degree of environmental improvement in counties that adopt industrial poverty alleviation is 22.2%, and the degree of environmental improvement in counties that adopt ecological compensation is 19.4%. It can be seen that the environmental improvement of counties that adopt industrial poverty alleviation is the most obvious, and the degree of environmental improvement of counties that adopt industrial poverty alleviation is 2.8% higher than that of ecological compensation counties. This may be due to the superiority of industrial poverty alleviation, which is a policy that can solve the root causes of poverty at the source, and can transform the "green mountains" in poor areas into "golden mountains", so that ecological advantages can be transformed into industrial advantages and economic advantages, instead of fishing for the environment. The way to get rid of poverty by destroying the environment (Chien et al., 2022; Lei et al., 2021). In fact, the industrial poverty eradication policy is more in line with the NBS development philosophy, constantly supported and utilized by nature, and aims to address poverty in a resource-efficient and adaptable way, while providing economic, social and environmental benefits to poor areas (Maes and Jacobs, 2015; Pan et al., 2021). The development of poverty-alleviation industries can accumulate funds for the development of other social projects. Moreover, the development of poverty alleviation industries can accumulate funds for the development of other social projects in rural areas, which objectively supports other poverty alleviation policy and contributes to the implementation of environmental protection policy (Lei et al., 2021; Shi et al., 2022; Zhang et al., 2022). Specifically, some scholars argue that some industrial poverty alleviation policy (F. B. Huang et al., 2022), such as photovoltaic poverty alleviation in developing countries, can promote sustainable development, improve the overall wellbeing of beneficiaries, and achieve the dual goals of poverty alleviation and green development, while some scholars argue that tourism can be developed to alleviate poverty by involving farmers in the development of local tourism industries and gaining income (Medina-Munoz et al., 2016), exploring the path to transform the "green mountains" in poverty-stricken areas into "silver mountains". Because the poor areas on the Qinghai-Tibet Plateau are in areas with harsh natural environment, poor basic conditions for economic development and fragile natural ecology, many areas are prone to natural disasters, which seriously affect economic and social development, but, on the other hand, most of these areas are scenic areas, not only with beautiful and unique natural scenery, but also with different ethnic customs because they are mostly inhabited by ethnic minorities, and of course, there are many Of course, many of these areas are also the upper reaches of large rivers and are in important national ecological function zones (restricted and prohibited development zones), which are crucial to the sustainable development of downstream areas and developed regions. These areas rely on natural and humanistic landscapes to develop tourism industry, which is to use this characteristic landscape product as a commodity to realize its economic value, and truly make "green water and green mountains are the silver mountain of gold" a reality. However, since poverty alleviation is a prerequisite for ecological improvement, ecological compensation policy has built-in poverty reduction measures, so when the economy of poor areas has not yet reached the poverty line, poverty reduction is still its main goal, and ecological improvement requirements are relaxed, so its environmental improvement effect is slightly weaker than that of industrial poverty alleviation policy. The choice of the type of poverty alleviation policy leads to different improvement effects, and this variation provides some reference value for other poor countries and regions in terms of what kind of poverty alleviation approach to adopt.

5 Conclusions and policy recommendations

It is of great theoretical and practical significance to accurately grasp the policy effects of poverty alleviation policies on the ecological environment, in order to further promote the coordinated growth of economic and ecological environment quality, and to provide lessons for the development of other poor areas. In this paper, using the poverty alleviation policy as a quasi-natural experiment and based on the panel data of poverty-stricken counties in the Qinghai-Tibet Plateau region from 2011 to 2019, the theoretical mechanism and impact effects of the poverty alleviation policy on the improvement of the ecological environment quality are examined in depth using the difference-in-differences model. The findings of this paper include: first, the poverty alleviation policy significantly improves the quality of the ecological environment in the Qinghai-Tibet Plateau region; second, the main transmission mechanism comes from the implementation of the poverty alleviation policy, which raises the level of public spending and relieves government fiscal pressure, which in turn improves the quality of the local ecological environment. Third, further heterogeneity analysis results show that: 1) The adoption of different types of ecological poverty alleviation policy has obvious differences in the effect of ecological environment improvement in counties, and each county needs to choose the most suitable way to get rid of poverty according to its natural endowment and actual needs. 2) The more advanced the industrial structure, the more obvious the improvement of ecological environment quality, which indicates that the local government needs to increase capital investment and control, promote industrial upgrading, and realize the coordinated development of environment and economy. 3) Administrative area and altitude also affect the effect and degree of environmental improvement, so policy should not be applied across the board, but should be tailored to local conditions, and more investment and assistance should be provided to the hard-to-reach areas. In addition, a series of robustness tests were conducted in this paper, indicating that the measurement results are stable and reliable.

Essentially, behind the fact that economic growth may be detrimental to ecological environmental quality reflects the long-standing contradiction and conflict between economic development and ecological environmental protection. This paper assesses the environmental impacts of poverty eradication policies on poor regions and analyzes the related impact mechanisms, which can clarify whether poverty eradication policies can achieve their economic-environmental synergy and can provide corresponding references for the implementation and formulation of SDGs and NBS strategies in other poor regions. The findings of this paper have the following three policy implications: First, within the Poverty-stricken counties of the Qinghai-Tibet Plateau under the influence of the poverty alleviation policy, economic growth does not damage the quality of the local ecological environment, which implies that the contradiction and conflict between economic development and ecological environmental protection is not irreconcilable. This means that the contradiction and conflict between economic development and ecological protection are not irreconcilable. This shows that in poor areas of China, ecological environmental protection and economic development can be organically combined and complementary, and that the "win-win" situation of "both green water and green mountains and golden mountains" can be achieved, and the goal of continuously supported by and using nature can be realized. Second, for the improvement of ecological environment quality, the most important thing is financial security, to solve the financial pressure of the local government, otherwise, the county government may not be able to provide adequate supplies, and the intervention and coordination of the higher government can solve this problem, so we should increase the transfer payments and policy support to poor areas, to encourage the local government to generate income and development, to form a virtuous circle; Third, after the financial pressure is solved, the government Third, after the fiscal pressure is solved, the government should also "dare to spend money" and increase public spending. The government is the main force in improving public goods and the environment, so it can consider including environmental protection indicators in the local government assessment to encourage the government to increase investment; finally, it is necessary to reasonably and orderly guide the transfer of labor to secondary and tertiary industries, encourage the low-carbon transformation of enterprises and promote the upgrading of local industrial structure, combine local natural endowments and actual needs, and choose the right type of poverty alleviation policy, so as to achieve poverty In this paper, we have proposed a scientific and systematic approach to the development of poverty alleviation policy in the region. In summary, this paper scientifically and systematically evaluates the effects of poverty alleviation policy, which can provide useful experiences and references for other poverty countries and regions to realize economic development and ecological environmental protection at the same time.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: National Earth System Science Data Center of China.

Author contributions

Conceptualization, writing—review and editing, RR; methodology and formal analysis, ZN; data curation and writing—original draft preparation, LH; project administration, TL. All authors have read and agreed to the published version of the manuscript.

Funding

This research was funded by National Natural Science Foundation of China (72074035); Fundamental Research Funds for the Central Universities (2022CDSKXYGG006); Graduate Research and Innovation foundation of Chongqing, China (CYS22100, CYB22057).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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frontiers | Frontiers in Environmental Science

TYPE Review
PUBLISHED 04 January 2023
DOI 10.3389/fenvs.2022.1089438

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OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Environmental Economics and Management, a section of the journal Frontiers in Environmental Science

RECEIVED 04 November 2022
ACCEPTED 16 December 2022
PUBLISHED 04 January 2023

CITATION
Li J and Song W (2023), Review of rural settlement research based on bibliometric analysis.
Front. Environ. Sci. 10:1089438.
doi: 10.3389/fenvs.2022.1089438

Review of rural settlement research based on bibliometric analysis

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Rural settlements are important rural land use types, and rural transformation and reconstruction are global issues in the process of urbanization. Research on rural settlements has been performed form different perspectives. In this paper, we took articles on rural settlements published in the core collection of Web of Science from 1973 to 2021 as the object of measurement analysis. Literature induction was used to determine the research progress, using the Bibliometrix measurement software. We also summarized the number of published papers, authors, research institutions and cooperative relationships, and keywords and investigated the theme evolution in the field of rural settlements. The following main results were obtained: 1) the number of articles related to rural settlements published was 1,703; the time from 1973 to 2021 can be roughly divided into three evolutionary stages: the initial stage (1973–1990), the development stage (1991–2010), and the high-yield stage (2011–2021). The number of articles published increased sharply after 2011, indicating that this research field received increased attention. 2) China and the United States published the largest number of articles in this field, followed by Australia. 3) In recent years, "Immigration," urbanization," "Land use," and "Floating population" were the most frequent keywords. Clustering analysis revealed four research. 4) Research in rural settlement areas changed largely over time; currently, in the context of urbanization, scientists focus on the renovation of rural settlements.

KEYWORDS

rural settlements, bibliometrics, bibliometrix, theme evolution, rural land renovation

1 Introduction

As the main rural population settlement type and the spatial unit of rural population activities, the rural settlement plays a crucial role in rural economy and society (Phillips, 1998). Research on the coordinated development of regional agriculture and rural areas and the balanced development of industry and urban areas has become an important field in geographic development (Deng et al., 2021). Rural settlements, as the core of rural human and land relations, have attracted great attention in recent years as the main areas of rural peoples' activities. The main contents of the theoretical system of studying rural settlements include rural geography, rural sociology, rural economics, and rural ecology (Long et al., 2020).

With the rapid development of the economy and society in rural areas, the distribution characteristics and spatial structure of rural settlements are constantly evolving, resulting in a scattered layout, and lack of planning; in some cases, the cultivated land area is threatened (Whatmore, 1993; Zhang et al., 2014). Politicians and scientists are therefore highly concerned about the further development of this phenomenon, and rural settlement land use has been studied extensively (Sevenant and Antrop, 2007). Urbanization has intensified the competition between rural settlements and other land use types. For example, the expansion of rural settlements frequently results in the occupation of surrounding farmland (Bibby, 2009), causes the degradation of forest land and grassland area (Kohler et al., 2015), and negatively impacts wetlands (Brady and Flather, 1994). At the same time, with the increasing recognition of the importance of these issues at a global level, the spatio-temporal evolution of rural settlements has been investigated extensively. Relevant studies mainly focused on the evolution and development characteristics and mechanisms of rural settlements as well as the impacts of socio-economic and political systems. Current research hotspots are the driving factors of rural settlement changes, location selection, layout optimization, landscape and ecological environment protection, and the potential analysis and sorting mode selection of rural settlement consolidation (Huang et al., 2020; Li et al., 2021).

Globally, studies on rural settlements mainly consider their formation, location, function, and land use types (Kiss, 2000; Thorsen and Ubøe, 2002; Nepal, 2007; Song and Deng, 2017), with emphasis on the methods of various disciplines and the influences of cultural and socio-economic factors on rural settlement development (Song and Pijanowski, 2014). For example, Vesterby and Kru Pa investigated the changes in rural settlement use and urban construction land use in the United States from 1980 to 1997, whereas Ruda found that agricultural industrialization resulted in a trend toward concentrated residences. Over time, the scale of new villages gradually expanded, whereas numerous small villages were abandoned and gradually disappeared, leading to changes in the layout and structure of regional rural settlements.

Since the 21st century, studies on land use/cover change (LUCC) have been strongly promoted internationally. In addition, the implementation of the Global Land Plan (GLP) project and various environmental issues have received widespread attention, and research on the spatial and temporal patterns of rural settlements, evolution simulation, and other aspects has become more comprehensive. In China, research on rural settlements started in the 1960s, mainly focusing on architecture. In the 1990s, China began to carry out research on traditional residential culture from the perspective of history and folklore (Whatmore, 1993; Li and Hu, 2019), followed by the quantitative research and spatial analysis of rural settlements in the 21st century. In recent years, important achievements have been made in the aspects of rural residential spatial distribution (Guo et al., 2020; Jiang et al., 2022; Sun et al., 2022), residential spatial pattern evolution (Dong and Xu, 2020; Shi et al., 2022), residential hollowing because of the rural population outflow (Sun et al., 2011; Guo et al., 2022), and the consolidation of rural settlements (Qu et al., 2019). In the context of global urbanization, rural settlements face drastic differentiation and restructuring, facilitating rural transformation and development.

Bibliometry is a method of quantitative literature analysis in a certain field with the help of mathematics and statistical tools. Visualization tools are combined to explore the research subjects, objects, themes within a given field and to analyze their interrelationships and influences (Aria and Cuccurullo, 2017). The field of rural settlements has obvious cross-disciplinary characteristics, and this review focuses on the qualitative summary of existing research results. However, a single summary cannot sufficiently evaluate the development process and trend of the research field from a macro-perspective. Generally, research results can be summarized using data mining, network analysis, scientific measurement, and mapping. In the software tools for bibliometric analysis, BibExcel tool cannot realize data visualization. Although CiteSpace has a strong visualization ability and unique advantages in keyword collinear analysis, its operation is complex. The operation of VOSviewer is simpler, but its data filtering and visualization level are limited. The Biblimetrix tool is based on the R language for statistical data analysis and has the advantage of rapid visualization. We therefore adopted this tool to quantify articles in the field of rural settlements from 1973 to 2021. Precisely, we analyzed the changes in the number of articles over time, the historical reference relationship of the article, the distribution of the author and its national/institutions, the number of published documents, and the distribution of high-frequency keywords. The following questions are addressed in this study:

(1) How are the relevant research keywords in the field of rural settlements clustered?
(2) Which countries have cooperated in rural settlement research?
(3) What is the trend of the article citation history in the field of rural settlements?
(4) What is the focus of future research in the field of rural settlements?

2 Research methods and data sources

2.1 Data sources

Web of Science is the most disciplinary comprehensive academic information resource in the world, including more

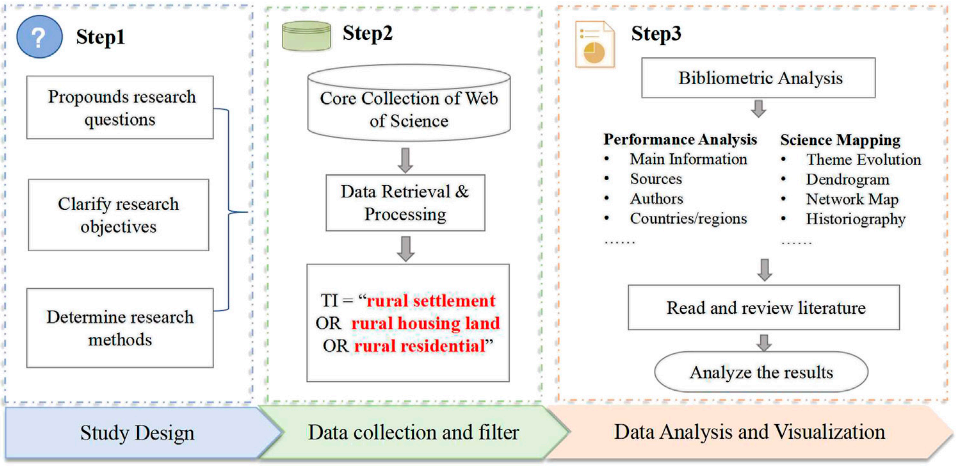

FIGURE 1
Research design and workflow.

than 12,000 core academic journals in various fields such as natural science, social science, arts, and humanities, reflecting the mutual relationship among different documents. We took the core collection in the scientific database Web as the data source and searched the journals using the advanced retrieval function. The Web of Science category was limited to "geography," "urban research," and "regional urban planning," and the search term was "rural settlements," using the so-called Topic Subject (TS) method. Considering the differences in different wording habits, the search was carried out with the search formula "TS = (rural settlement OR rural housing land OR rural residential)." The document type was limited to "articles" published from 1973 to 2021, spanning approximately 50 years. Overall, 1,703 articles in the field of rural settlements were obtained.

2.2 Research methods

Bibliometric analysis is increasingly used in academia to obtain quantitative results in the development of specific (sub-) areas of scientific inquiry. By visualizing various indicators containing quantitative information for a given field, scientific measurement mapping allows to obtain a deeper insight and is therefore a useful approach in ever-changing science. This paper used the R Bibliometrix tool to study the field of rural settlements (Du and King, 2018), targeting 1,703 research articles published from 1973 to 2021.

A Bibtex file was created using the Bibliometrix quantitative method, along with data analysis and visual expression (Figure 1). The first step was to develop the research design, establish the research questions, clarify the research objectives, and determine the research methods. The second step was data collection and filtering. Based on the Web of Science™ core collection, the literature was searched for publications in the field of rural settlements, the results were screened, and irrelevant articles were removed. The third step was data analysis. First, we imported the data into Bibliometrix for analysis, including information analysis and scientific mapping, and then analyzed and visually expressed the research subjects (such as authors, journals, institutions). Subsequently, we carefully read the retrieved articles and discussed and analyzed the research hotspots and frontiers *via* keywords.

3 Results

3.1 Quantitative statistics and article source analysis

3.1.1 Annual change analysis of article quantity

The changes in the number of articles over time can reflect the general trend of the overall development of the research field. According to the time series analysis of the distribution trend of the annual number of articles published regarding rural settlements, the average annual growth rate was 11.44% (Figure 2). The number of articles published in the field of rural settlements could be divided into three stages: initial stage, development stage, and high-yield stage. The initial stage lasted from 1973 to 1990, with a small number of publications, indicating that the field of rural settlements received less attention. During this stage, studies mainly focused on the qualitative description of the definition, formation process, and development history of rural residential areas (Lewis and Mrara, 1986; Hingley, 2004). Although the number of research articles was small, the discussion about the concept and theoretical framework has

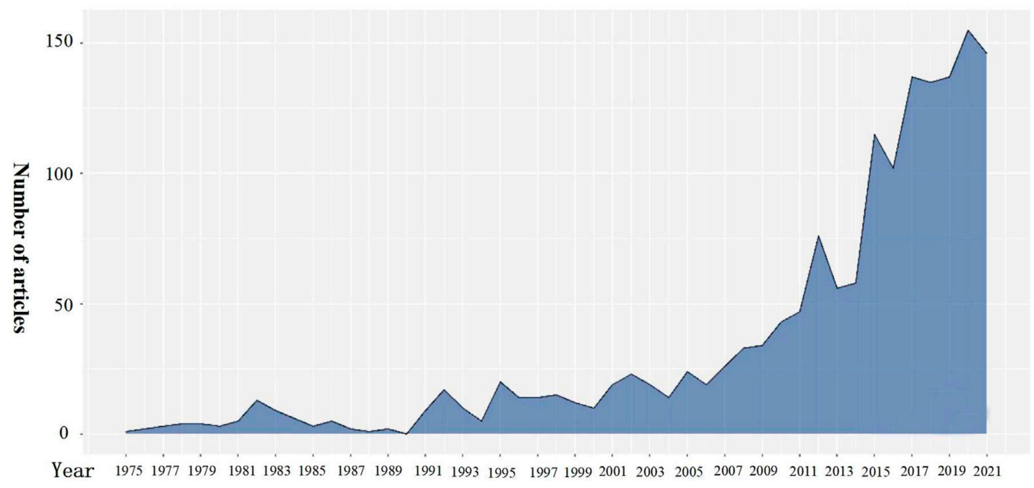

FIGURE 2
Number of rural settlements research articles from 1973 to 2021.

laid a foundation for subsequent research. From 1991 to 2010, the number of published articles increased slowly, indicating that this research field attracted more attention; however, the annual number of published articles still did not exceed 50. During this period, with the development of the rural economy and an increasing awareness about environmental issues (Whatmore, 1993), scientists started to study the distribution characteristics and influencing factors of rural settlements, and relevant research gradually became more diverse. The number of publications increased exponentially from 2011 to 2021, reaching 146 publications in 2021, which is about three times higher than that in 2011. With the continuous broadening of the research perspective, results regarding the evolution and development characteristics of rural settlements as well as the impacts of social economy and the political system on changes in rural settlements were obtained (Mann, 2009; Bittner and Sofer, 2013; Yang et al., 2016).

3.1.2 Analysis of the article sources

The study of rural settlements includes numerous disciplines such as economy, environment, agricultural engineering, and architectural science. International papers on rural settlement research were mainly published in English-speaking journals related to human settlement and rural-urban research, such as *Habitat International*, *Journal of Rural Studies*, and *Landscape and Urban Planning*, among which *Habitat International* has the largest number of papers, 114 in total (Table 1). Articles in journals related to rural and urban studies were the most cited ones, such as those in the *Journal of Rural Studies* with 1,738 citations, *Urban Studies* with 1,364 citations, and *Landscape and Urban Planning* with 1,304 citations.

Regarding the cumulative number of articles from different journals, *Landscape and Urban Planning* published the most articles from 1973 to 2021. After 2018, the growth rate of articles published by *Habitat International* and *Journal of Rural Studies* surpassed that of *Landscape and Urban Planning*. At the same time, the two journals *Cities* and *Population Space and Place* also published considerably more articles compared to 2010. This indicates a substantial increase in the degree of attention in the past 10 years (Figure 3). From the perspective of the research topics of articles published in different types of journals, we summarized the differences in the development of rural settlements in different fields in the past 50 years. Articles published by *Habitat International* mostly focused on the suitability assessment of the rural residential distribution and regional classification, whereas *Landscape and Urban Planning* and *Cities* mainly published articles investigating the impacts of urbanization on rural settlements and landscapes. Articles published in the *Journal of Rural Studies*, *Applied Geography*, and other journals generally had a wider research perspective, such as the evolution of rural settlement models, the willingness of farmers to relocate, and the architectural characteristics of rural settlements.

3.2 Historical citation analysis of rural settlement research

The numbers of citations and downloads are of large interest for academic journals and readers. When a publication is widely cited or heavily downloaded, this reflects the influence and academic level of this publication, at least to some extent.

TABLE 1 Top 10 LCS literatures in the field of rural settlements.

Journal name	Number of articles	Impact factor
Habitat International	114	5.205
Journal of Rural Studies	112	5.157
Landscape and Urban Planning	97	8.199
Cities	56	6.077
Population Space and Place	52	1.718
Urban Studies	50	3.850
European Countryside	49	1.461
Applied Geography	36	4.732
Geoforum	23	3.926
Journal of Transport Geography	21	5.899

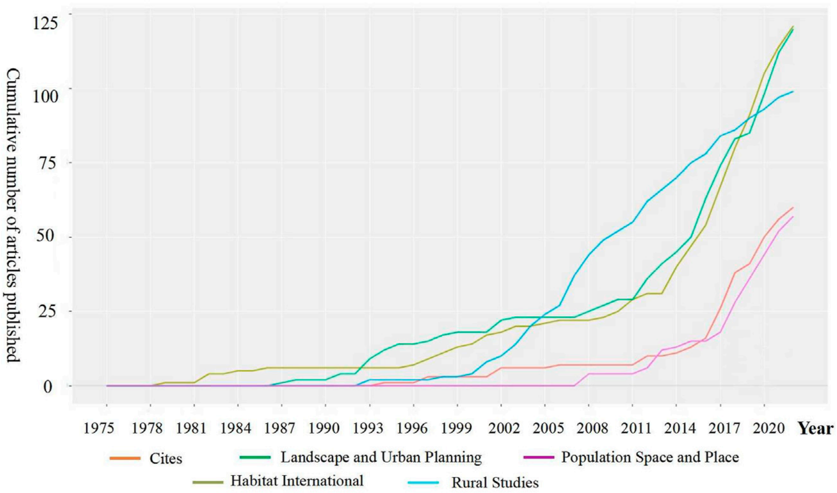

FIGURE 3
Time dynamics of publication volume of different journals in the field of rural settlements.

Statistical analysis of the citation volume and downloads could reveal a hot topic, important development direction, and trends in a given field. We used the "Historiography" module of Bibliometrix to visualize the historical citations in the field of rural settlements, and 20 nodes were selected to find classical studies in this field.

We used the indicators Global Citations (GCS) and Local Citations (LCS) to analyze the degree of attention and influence of classical studies. Whilst LCS is a reference in the downloaded paper dataset, GSC represents a reference in the scientific core set database. Among the studies on rural settlements published from 1973 to 2021, the most frequently cited article was one published by Yansui Liu, a researcher from the Chinese Academy of Sciences, in *Habitat International* in 2010 (Liu et al., 2010), with 270 international and 34 national citations (Table 2), reflecting its research and reference value. Relevant institutions and researchers paid considerable attention to the issue of rural settlements, and most of the research results were published in high-ranking journals.

The field of rural settlement research featured many classical articles from 1973 to 2021. An article published in the *Journal of Rural Studies* in 1988 showed that against the background of the reduction of the rural population in Japan after the First World War, the country explored how to solve the social problem of population decline in remote rural areas

TABLE 2 Top 10 journals with local citation in the field of rural settlements.

DOI	Year	Local Citations (LCS)	Global citations (GCS)	LCS/GCS ratio (%)
10.1016/j.habitatint.2009.08.003	2010	34	270	12.59
10.1177/0308518X15597131	2015	34	67	50.75
10.1177/0042098007085965	2008	28	153	18.30
10.1016/j.landurbplan.2013.08.016	2013	27	88	30.68
10.1016/j.habitatint.2015.06.009	2015	27	62	43.55
10.1177/0042098016634979	2017	27	63	42.86
10.1016/j.landurbplan.2009.08.005	2010	24	79	30.38
10.1177/0042098012466600	2013	24	204	11.76

Note: Local citations (LCS), global citations (GCS).

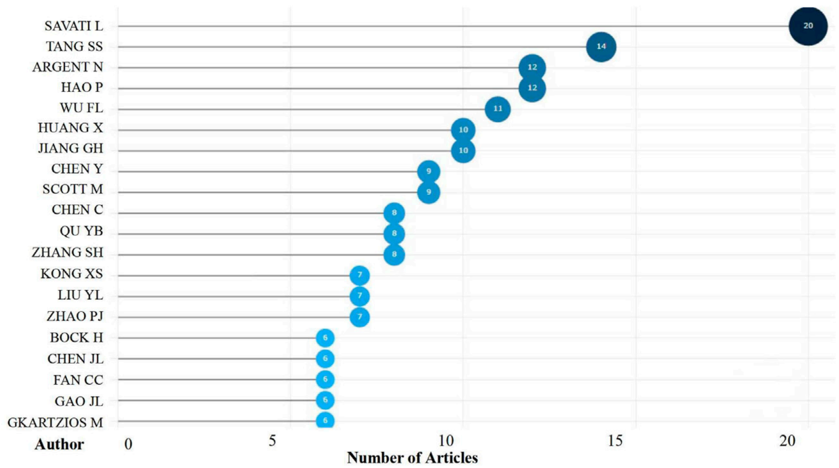

FIGURE 4
Number of articles published in the field of rural settlements research.

by implementing the planned relocation scheme of rural settlements. Hao and Tang (2015) published an article in *Environment and Planning* in 2015, with the highest local citation frequency of 39 times. The authors showed that the arable land and house share of rural residents have the greatest impacts on the willingness of rural residents to relocate. At the same time, the gap between rich and poor and the intergenerational differences are also important reasons for relocating. Given the pressure excised by urban areas, the mode, driving force, and policies of rural settlements have also been largely investigated (Song et al., 2008; Tan and Li, 2013), along with the factors that impact the willingness of rural residents to relocate (Tang and Feng, 2015; Liu et al., 2017a). The most frequently cited articles were mainly published around 2010, indicating that at this time, many important achievements were made in research on rural settlements.

3.3 Analysis of key researchers and institutions

3.3.1 Researcher analysis

The data set used in this study involved 2,541 authors, among which Salvatil L, Shuangshuang Tang, and Argent N were the top three ones, with 20, 14, and 12 papers published, respectively (Figure 4). The largest number of articles was published by Salvati L, with a total of 135 citations, demonstrating the high quality and great impact of publications from this author. Salvati L's most frequently cited paper appeared in 2016, with 28 citations (Figure 5). In 2012, this author published an article in *Landscape and Urban Planning*, analyzing the impacts of urban expansion models at different stages on the use of rural land. Shuangshuang Tang's most frequently cited paper, published in *Habitat International*, also appeared in 2016. The authors

FIGURE 5
Authors' Production during 2001–2021 in the Field of Rural Settlements. Note: N. Article is the number of articles; TC per Year is the total number of citations per year by the author.

conducted a field survey in the suburbs of Nanjing, China, in 2016, to investigate the land transfer and the willingness of rural residents to relocate, showing that abandoning farmland and housing is determined by different factors. The authors reported that villagers are largely opposed to the existing land conversion policy. Because the willingness to give up original land and settle in another region is jointly determined by socio-economic, local culture, future development prospects, and other factors, only considering the compensation scheme is not sufficient (Salvati et al., 2012). McManus et al., 2012. conducted field research in the state of New South Wales, Australia; based on a collection of farmers' intentions to relocate, the authors proposed a future reflection on how to respond to the declining population trend in rural areas. In this study, the importance of increasing rural resilience in the face of economic and environmental challenges is emphasized.

Considering the change in the number of publications over time, we analyzed the timeline of the authors' output in a given field (Figure 5). Wu FL is the author with the longest research period in the field of rural settlements, with articles published from 2001 to 2021. In 2010, the authors published four articles, with an average annual citation rate of 44.8. His most cited article, which presents a novel stochastic CA model to analyze urban-rural land conversion in Guangzhou, China, has 407 citations. Jiang GH started his research on rural settlements late but has a high number of publications and citations. The author published research results on rural land use transition, rural residential land use in suburban areas, and sustainable rural development. After 2015, Huang X, Zhang SH, and many other authors started to focus on the field of rural settlements, maintaining a steady publication output. It goes without saying that the number of articles is not proportional to the number of citations. Although the number of articles on rural settlement research continues to increase, classical highly cited articles are still scarce. In the future, more attention should therefore be paid to the publication of high-level articles.

3.3.2 Major research institutions and cooperations

The distribution characteristics of the main study countries/regions reflected the influences of different countries/regions on research in the field of rural settlements and provided the conditions for the different degrees of influence in further development. The top 10 countries in terms of the number of articles published were China, the United States, the United Kingdom, Australia, Brazil, Canada, Spain, Germany, the Netherlands, and Italy, mainly in Asia, Europe, and Oceania (Table 3). The number of articles published by China and the United States was considerably higher than that of other countries, indicating the high achievements of these two countries. In the context of the large rural population of China (500 million rural residents), research on rural settlements has a long history (Wang and Fang, 2011). Especially after the Chinese government put forward the National New-type Urbanization Plan in 2014 (Li and Song, 2020), many studies on the evolution characteristics of rural settlements emerged, analyzing the impacts of the new urbanization policy on rural settlements. In this country, rural settlements are undergoing tremendous changes. Regarding the influence of urbanization, scientists focus on the non-agricultural transformation of the rural population, the impacts of population migration on land use, and other issues. At the same time, the changes in rural functions caused by the non-agricultural transformation of the rural population and the transformation of the residents' lifestyle are also issues commonly studied at a global level.

The number of scientific and technological papers published is one of the important indicators to measure a country's

TABLE 3 Number of articles in rural settlements field in different countries/regions published.

Country/Region	Number of articles	Country/Region	Number of articles
China	699	Hungary	68
United States	511	Turkey	60
United Kingdom	246	France	59
Australia	149	Czech Republic	51
Brazil	135	Norway	48
Canada	122	Poland	47
Spain	108	Ireland	45
Germany	99	Portugal	42
Netherlands	99	Sweden	41
Italy	79	South Africa	33

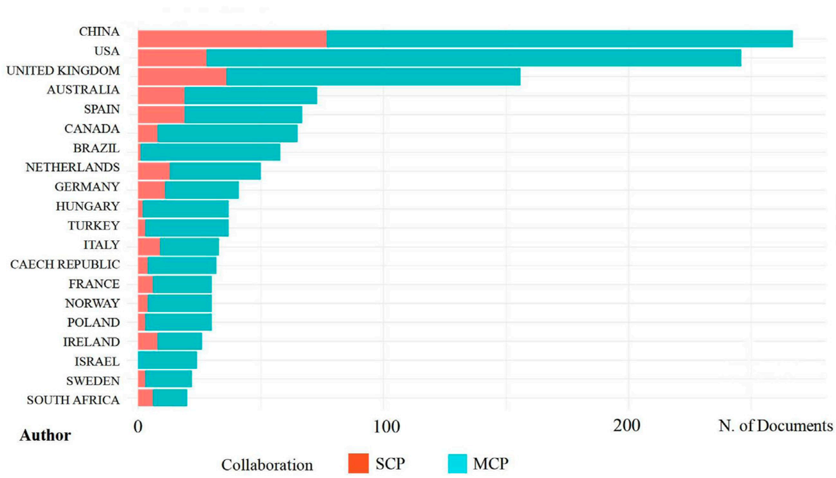

FIGURE 6
Nationality of the corresponding author in 20 high-yield countries in the field of rural settlements.

scientific research strength. The SCP, the number of authors from the same country, and the MCP, the number of publications from different countries, could be further used to analyze the scientific research strength of different countries. During the investigation period, China had the highest MCP with 78, while the United States had the highest SCP with 223 (Figure 6). This indicates that the number of independent papers published by Chinese authors was lower than that of papers published in cooperation with other authors, highlighting the importance of international collaboration in China. For example, Yang et al. (2016) published an article in *Rural Studies* in 2014, summarizing the typical distribution patterns of rural settlements in China: Including radial balance, the central land distribution model, the radial unbalanced distribution model, the multi-core central land distribution model, as well as the corridor balanced and unbalanced distribution model. As seen in the national collaboration network (Figure 7), China significantly contributed to international collaborations, mainly with the United States, Australia, and New Zealand, with 40, 20, and 17 collaborations, respectively, accounting for 32%, 16%, and 15% of the total Chinese collaborations, respectively. The countries with the highest numbers of co-published articles were China, the United Kingdom, and the United States, with 74, 36, and 28 articles, respectively, accounting for 25%, 12%, and 9% of the total co-published output. China and Spain published a large number of articles independently, whereas Germany, the United Kingdom, and the Netherlands focused on collaborative research. Although China had the highest number of articles

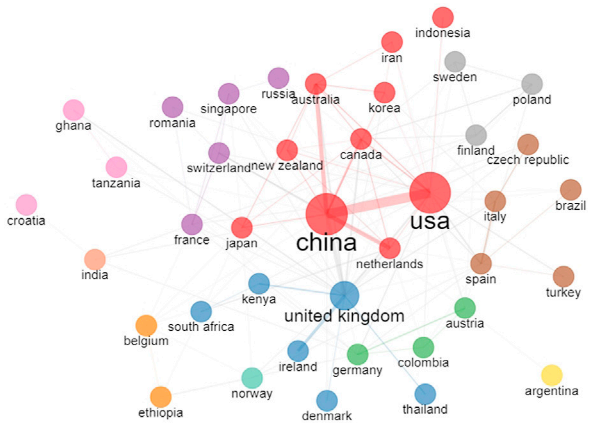

FIGURE 7
National collaborative network for research on rural settlements. Note: The size of the circle represents the number of articles published in cooperation with other countries, and the thickness of the connecting line represents the number of cooperation between countries; the thicker the line, the closer the connection between countries.

FIGURE 8
Rural settlements field high -frequency keyword cloud map.

published (699), the average annual citation count was 27.6, lower than that of 33.9 in the United States. This suggests that, although Chinese authors published a large number of articles in the field of rural settlements, the international impact of this research needs to be improved.

3.4 Keyword analysis

3.4.1 High-frequency keywords

Keywords provide the most simple and clear expression of the core content of an article. Analyzing the frequency of keywords in a certain field can therefore help summarizing the themes and hotspots of research in this field. We statistically analyzed the keywords in the field of rural settlements and generated the word cloud map of keywords. “Immigration,” “urbanization,” and “land use” were the keywords that most frequently appeared (Figure 8), accounting for 13%, 12%, and 7% of the total keywords, respectively. The keyword “China” accounted for 5% of the keywords, indicating that a large part of research was performed in this country. This corresponded to the number of articles analyzed above and the status of international cooperation in China. The frequencies of the keywords “policy” and “management” were also high, indicating that rural residential research was highly related to policy factors. At the same time, the research results on the evolution and simulation of rural settlements were linked to policies. For example, Yang et al. (2016) studied the spatial distribution characteristics and optimization analysis of rural settlements against the policy background of China’s rapid urbanization. Tu et al. (2018) took Huang Shandian Village in Beijing as an example and studied the adjustment of the village-level rural structure under the rapid urbanization in the metropolitan suburbs of China.

The most frequently found keyword in rural settlement studies was “migration,” which showed that population flow was one of most important reasons for the changes in rural settlements. For example, Chen et al. (2014) analyzed the impact of China’s rural population emigration on the transformation of rural settlement land, stating that the large-scale population flow between different regions led to the transformation of land use. Future studies on the impact of rural emigration on rural settlement areas should therefore take a multi-scale perspective (Chen et al., 2014). The research focus of each country will vary over time. For example, rural areas in the United States are mainly family farms, and the trend of agricultural specialization and intensive production is obvious. Therefore, keywords such as “Landscape” and “Life countryside” appeared frequently in relevant studies. “Land Use” and “Land Consolidation” have received a high degree of attention in studies of rural settlements in China. Although the word “Rural Hollowing” did not appear frequently, the hollowing and abandonment of rural settlements in China has attracted great attention. “Urbanization” appeared frequently in studies from almost all countries. Germany, Great Britain, and other European countries started their research on rural settlements early, and almost all developed countries carried out rural settlement renovation. Therefore, the rural development models of these countries have reference significance for countries with low rural development levels.

3.4.2 Cluster analysis of high-frequency keywords

Cluster analysis, also known as group analysis and point group analysis, is a multivariate statistical method for studying

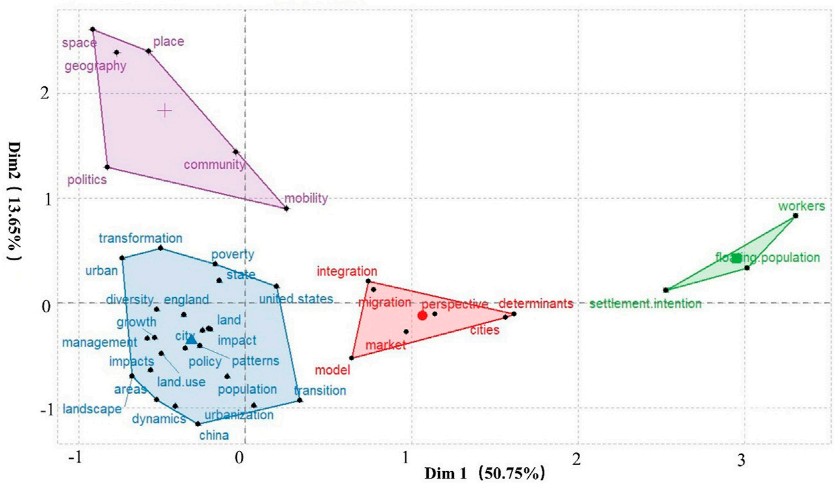

FIGURE 9
Multiple correspondence analysis of high -frequency keywords in rural settlements fields.

classification. Cluster analysis in bibliometry is based on the simultaneous frequency of two or two keywords, using statistical methods to reduce complex keyword grid relationships to several relatively small class groups; it first appeared in the 1960s (Blasius et al., 2009). This analysis type is an exploratory approach to graphically represent the associations among variables in large taxonomic datasets, with the aim to explore their relationships. In this study, the keywords with the highest similarities were merged into one cluster, and the clustering results of multiple corresponding analyses in the field of rural residential areas were divided into four categories (Figure 9):

(1) The first category was mainly related to geography, space, place, policy, and community. Studies in this category mainly investigated the spatial and temporal differences as well as the influencing factors and policy recommendations of rural settlement distribution in the field of geography (Song and Li, 2020). For example, Song and Li (2020) studied the spatial pattern evolution of rural residential areas in Tongzhou District, China, from 1961 to 2030, based on remote sensing image data; four evolution patterns of rural settlements in different periods were analyzed. Based on actual survey data, Qu et al. (2017) used spatial auto-correlation and spatial econometric models to quantitatively characterize the spatial differentiation and multifunctional structure of rural settlements, revealing the formation mechanism of rural multi-functionality.
(2) The second cluster was mainly related to urbanization, land management, land use transformation, and poverty. “China” and the “United States” also appeared as cluster keywords, indicating that these two countries played an important role in relevant research. Urbanization has a great impact on rural residential areas, and Liu et al. (2017b) discussed the dynamic spatio-temporal characteristics and trends of urban expansion in relation to the erosion of cultivated land and rural settlements. Understanding the changes in rural settlements due to radiation exposure during urbanization could help governments formulate relevant rural development policies.
(3) The third cluster was related to the improvement of rural settlements and urbanization-induced changes in settlements, focusing on the migration of the rural population to cities and towns. For example, Tas and Lightfoot (2005) reported that most urban growth in Turkey was shaped by rural-to-urban migration. Research on the improvement of rural settlements was mainly performed in China, emphasizing the changes in rural settlements caused by the number of rural settlements, the adjustment of their layout, the adjustment of land use scale and internal structure, and conducted comprehensive research on the potential, mode, planning, and evaluation of rural settlements.
(4) The fourth category mainly involved relocation willingness, population mobility, and rural population employment. As the integration and extinction of rural settlements, caused by urbanization, greatly impacted the production level and lifestyle of the rural population, various social problems have also been widely investigated. For example, Chai and Choi (2017) studied the trend of rural-oriented (migration/mobility) population migration and mobility in the context of rural reconstruction in Turkey. Xie and Chen (2018) analyzed China’s housing conditions, housing support, and migrant workers’ urban settlement intentions and found that rural migrants with better living conditions

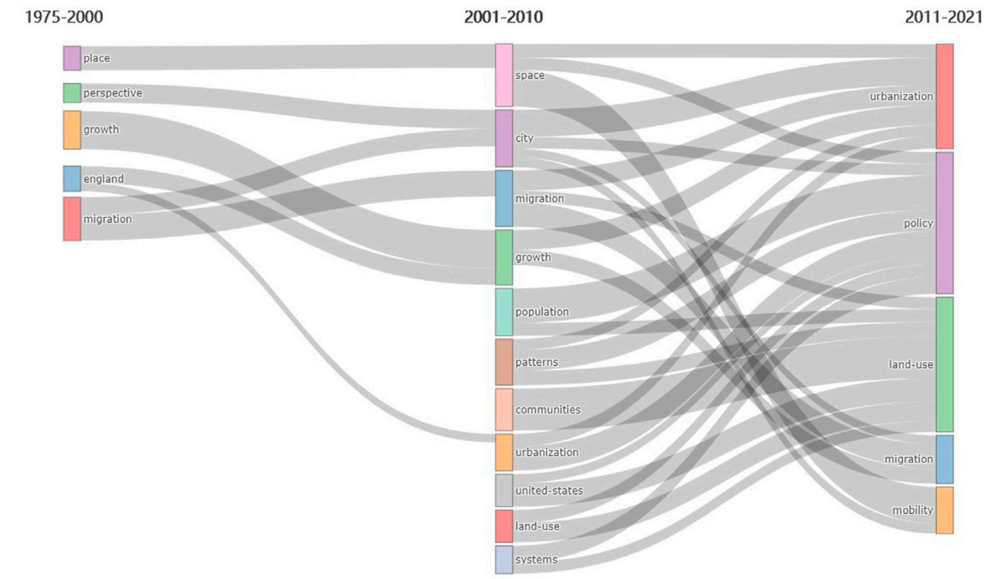

FIGURE 10
Theme Evolution of the Field of Rural Settlements from 1973 to 2021.

and housing support were more inclined to settle in cities. Although urban villages provide cheap housing for workers moving from rural areas, because of various urban problems, some authors proposed policy suggestions to encourage migrant workers to relocate from the perspective of sustainable urban development in China (Chai and Choi, 2017).

3.5 Analysis of the theme evolution in rural settlements

It is important to study the research development in a field from the perspective of themes and theme evolution (Weismayer and Pezenka, 2017). The Sankey chart, also known as the Sankey energy shunt, is a specific type of flow chart and can describe the flow of different nodes in the network; it is commonly used to analyze energy or matter flow. Arrows or direction lines indicate these flows, and their thickness is proportional to the flow size. The width of the extended branches in the figure corresponds to the extent of the data flow. This approach is mostly used in industrial ecology to assess the life cycle of a product and to determine the energy efficiency in engineering (Schmidt, 2008). Because of its broad utility, it has been applied in numerous geographic or environmental studies (Riehmann et al., 2005). Based on the Sankey diagram, we visually present the changes of themes in the research field of rural settlements over time. Referring to Chemchieva (2021), we divided the main transfer of rural settlement development into three stages, with 2000 and 2010 as breakpoints.

Rural settlement-related research topics changed over time (Figure 10). Before 2000, rural residential research was in the initial stage, and scientists started to explore the growth of residential areas and migration from the perspective of geography. During this period, the United Kingdom paid the most attention to rural residential research. From 2000 to 2010, the research scope gradually increased, studies focused on urban "population, land use change, community, and system, with a trend toward multidisciplinary and multi-perspective comprehensive analysis. Rural residential research from 2011 to 2020 mainly focused on land use change, urbanization, immigration, and policy. For example, Yang et al. (2016) pointed out that the optimization and reconstruction of rural residential space against the background of rapid urbanization was the key of rural sustainable development. Abubakari et al, 2016. stated that rural settlements need to formulate distinctive development plans based on regional characteristics, and rural land consolidation plays an important role in the study of rural settlements. Tu et al. (2018), using the example of Huangdian Village of Beijing, studied the gradual functional evolution of rural areas in the suburbs of metropolises. Through optimizing the allocation of land resources to promote the adjustment of the rural structure in metropolitan suburbs, suggestions were made for the innovation of land use policies and systems (Tu et al., 2018).

4 Discussion

4.1 Research trend

Rural settlements are the geospatial carriers of agricultural production, farmers' income and activities, and the rural ecosystem and at the core of the relationship between the rural population and the land. Based on previous studies of rural settlements, we found that rural settlement studies were mostly qualitative analyses of landscape descriptions in the initial period, and few studies began to focus on the planned changes of the reduction of rural settlements and population (Palmer, 1988). After 2000, rural settlements attracted an increase attention from the scientific community, and data acquisition and visual analysis methods were enriched with the wide application of the 3S technology (Remote sensing, Geography information systems, Global positioning systems). Important results were obtained in the research on the evolution law, influencing factors, spatial distribution patterns, and optimal layouts of rural settlements (Cao et al., 2017; Kong et al., 2021). In recent years, research on rural settlements has reached a multi-perspective and interdisciplinary level, with a rich research perspective.

4.2 Prospects

At present, research in the area of rural settlements is highly diverse. Future studies should focus on the investigation of rural settlements from the interdisciplinary perspective and enhance the cooperation among countries to include different perspectives. Since rural residential area renovation and rural revitalization have become hot issues, research on the interaction between rural settlement land change and nature, society, and economy is extensive. However, authors are encouraged to focus on the analysis of driving factors, such as the driving factors of rural "hollowing out," the relocation of rural collective migrants, and the rural ecosystem. As a basic social unit in rural areas, farmers are the main factors to consider in studies of rural residential area renovation, emphasizing on their ethnic customs, consumption habits, religious beliefs, original economic basis, and policy factors. In this context, the importance of rural settlement development for the diversity of human needs will gradually increase. Future studies should therefore focus on the exploration of spatio-temporal evolution mechanisms and trend prediction, supported by GIS technology. Based on strengthening theoretical practice, the analysis of the evolution pattern of rural settlements, the summary of different evolution models, and the analysis of influencing factors are crucial, with the aim to generate an extensive and systematic research system.

4.3 Comparison with previous studies

At present, the research perspective of rural settlements is multi-dimensional, with considerable achievements. Based on the results discussed here, most articles are based on a specific aspect; for example, from the perspective of specific disciplines (Phillips et al., 2008), specific research areas (Janusek and Kolata, 2004), and the development of major thought lines (Drobnjaković et al., 2017). Based on these studies, we can indeed understand the specific situation of rural settlements under a certain perspective, but it is difficult to establish a unified logical main line between different research perspectives. The systematic characteristics of the research field have been largely ignored, which impedes a comprehensive understanding of the overall research situation from a macro-perspective. Using the Web of Science database, which contains articles covering natural science, engineering technology, social science, and many other fields, we synchronously analyzed the existing literature based on results, authors, institutions, hotspots, and other perspectives. Through visual data analysis, we stereoscopically present information, avoiding information loss caused by the segmentation of the research angle and incoherent research processes, which are common in traditional literature research.

5 Conclusion

Based on the Web of Science database, we retrieved articles in the field of rural settlements published from 1973 to 2021 and used the Bibliometrix software to analyze them, obtaining the following conclusion:

(1) According to the annual output of articles, the development of rural settlement research could be divided into the initial stage (1973–1990), developmental stage (1991–201), and high-yield stage (2011–2021).
(2) Most of the articles in this field were published in Asia, Europe, and Africa. Countries with more than 100 articles published were China, the United States, the United Kingdom, Australia, Brazil, Canada, and Spain. China, which published the largest number of articles (699), was also the center of international cooperation in the field of rural settlement research, mostly together with the United States.
(3) High-frequency keywords in rural residential research were "Immigration," "Urbanization," "Land use," and "Population flow." Cluster analysis revealed four clusters: one related to

geography, space, place, policy, and community, one related to land management, land use transformation, and urbanization, one focusing on rural residential area renovation and residential settlement changes due to urbanization, and one related to residential intention, population flow, and employment of the rural population.

Based on our results, we encourage scientists to include the evolution of the spatiotemporal pattern of rural settlements, the transformation of rural land use, and the relationship between rural settlement changes and rural population in their studies.

Author contributions

JL and WS: Methodology, software, validation, writing. JL: Software, investigation, validation, data curation, writing-originaldraft. WS: Methodology, validation, project administration, writing-review and editing. All authors contributed to the article and approved the submitted version.

Funding

This research was supported by the Second Tibetan Plateau Scientific Expedition and Research (grant number 2019QZKK0603) and the Projects of National Natural Science Foundation of China (grant number 42071233 and 41671177).

Acknowledgments

The authors thank the native English-speaking experts from the editing team for polishing our paper.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 04 January 2023
DOI 10.3389/fenvs.2022.1078357

OPEN ACCESS

EDITED BY
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SPECIALTY SECTION
This article was submitted to Environmental Economics and Management,
a section of the journal
Frontiers in Environmental Science

RECEIVED 24 October 2022
ACCEPTED 12 December 2022
PUBLISHED 04 January 2023

CITATION
He H and Ding R (2023), Spatiotemporal heterogeneity effect of technological progress and agricultural centrality on agricultural carbon emissions in China. *Front. Environ. Sci.* 10:1078357.
doi: 10.3389/fenvs.2022.1078357

Spatiotemporal heterogeneity effect of technological progress and agricultural centrality on agricultural carbon emissions in China

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Reducing agricultural carbon emissions is an important aspect of achieving China's carbon peak and neutrality goals. Different agricultural centrality result in different agriculture status and role in different regions, affecting agricultural carbon emissions. In this study, agricultural centrality is introduced from the perspective of social network analysis. Spatial autocorrelation analysis, geographically and temporally weighted regression (GTWR) and other methods are used to empirically explore the effect of technological progress and agricultural centrality on the spatiotemporal heterogeneity of agricultural carbon emissions. The moderating effect of agricultural centrality on the relationship between technological progress and agricultural carbon emissions is further explored. The results show that 1) during the research period (2001–2019), the agricultural carbon emissions first increased and then decreased, with remarkable spatial agglomeration characteristics, revealing a significant spatial autocorrelation of carbon emissions among provinces; 2) provinces have distinctly uneven characteristics in the social network of agricultural carbon emissions, while the same province shows relative consistency in terms of location centrality and betweenness centrality. Areas with high centrality are the major grain producing areas, and they invariably play an important role in the spatially linked network of agricultural carbon emissions; 3) technological progress has an inhibitory effect on agricultural carbon emissions, and the regression coefficient decreases from western to eastern regions, demonstrating a spatial gradient distribution. The location centrality has a negative effect on agricultural carbon emissions, with significant spatial heterogeneity. The effect of betweenness centrality on agricultural carbon emissions has increased from positive to negative over time, and the promotion of each province's intermediary role has inhibited the increase of agricultural carbon emissions; 4) both agricultural location centrality and betweenness centrality have significant positive moderating effects on the relationship between technological progress and agricultural carbon emissions. With the increase of location centrality and betweenness centrality, technological progress has an increasingly strong inhibitory effect on agricultural carbon emissions. We put forward targeted suggestions based on different agricultural centrality in order to reduce agricultural carbon emissions and provide directions for achieving the China's carbon peak and neutrality goals and the Sustainable Development Goals of the United Nations' Agenda 2030.

KEYWORDS

agricultural carbon emissions, centrality, technological progress, GTWR, moderating effect

1 Introduction

With the global attention to climate change and environment protection, agricultural carbon emissions have received more attention. According to the latest data of United Nations' Food and Agriculture Organization, China's total agricultural carbon emissions in 2019 amounted to 667.45 million tons, accounting for 25.73% and 11.20% of Asia's and world's total agricultural carbon emissions, respectively. Agriculture is one of the important sources of global greenhouse gas emissions (FAO, 2022). The increase in agricultural carbon emissions not only affects the climate and environment, but also threatens the security of agriculture itself (IPCC, 2021). Promoting carbon neutrality in agriculture is a critical aspect of accelerating the construction of a sustainable agro-ecological civilization and an important consideration for comprehensively addressing climate change. Agriculture is affected by natural conditions, climate change and human activities (Carlson et al., 2017), with the characteristics of large regional differentiation and complex sources of carbon emissions. Therefore, considering China's carbon peak and neutrality goals, it is of great significance to reasonably measure agricultural carbon emissions, explore agricultural carbon emissions reduction measures based on China's conditions and accelerate the pace of low-carbon transformation of agricultural production.

To advance more effective and expedient low-carbon development of agriculture, many scholars have focused on the agricultural carbon emissions (Carlson et al., 2017; Zhao et al., 2018; Liu Z. et al., 2021; Yang H. et al., 2022). At present, the main focus of agricultural carbon emission reduction research is emission characteristics and its influencing factors (Bhattacharyya et al., 2012; Zhang et al., 2019; Xiong et al., 2021; Zhou et al., 2021). In terms of the characteristics of agricultural carbon emissions, agricultural carbon emissions in China generally show a downward trend (Yang H. et al., 2022), and they mainly concentrated in major agricultural provinces, with remarkable spatial aggregation. In addition, carbon emissions in some regions have a rebound effect (Tian et al., 2014; Chen J. et al., 2019). The agricultural carbon emission intensity shows a downward trend over time, and the decline rate in central and eastern regions is significantly faster than the western regions (Li and Li, 2022). In terms of research methods, various methods such as slacks-based measure (SBM) model (Kuang et al., 2020; Liu D. D. et al., 2021), exploratory spatial data analysis (Chen J. et al., 2019; Cui et al., 2021), input-output model (Wang et al., 2020) and scenario simulation (Shan et al., 2018; Liu and Feng, 2020) have been used in the research on structure, offset and spatiotemporal variation of agricultural carbon emissions.

In terms of influencing factors, some scholars have explored the impact of natural climatic conditions, economic development level labour input, agricultural resource input, and agricultural technology on agricultural carbon emissions (Xu et al., 2021; Yang et al., 2021; Yang H. et al., 2022). Studies have demonstrated that economic development increases agricultural carbon emissions, and labour input and technology input have a remarkable inhibitory impact on the agricultural carbon emissions, with a significant spatial spillover effect, which is a key factor to improve carbon emission performance (Yang H. et al., 2022). Some scholars have explored the impact of technological progress on agricultural carbon emissions. Due to different research periods, some studies found that technological progress has a significant inhibitory impact on agricultural carbon emissions (Liu and Yang, 2021). Agricultural technological progress has a strong diffusion effect (He et al., 2021; Li and Li, 2022). Most of the previous studies only analyse the overall effect and ignore regional heterogeneity when exploring the effect of technological progress on agricultural carbon emissions; GTWR model can uncover the spatiotemporal heterogeneity of technological progress on agricultural carbon emissions. In addition, each province's agriculture in each province is not independent, but has spatial network associations. The centrality in the agricultural social network can reflect regions' status in the social network (Shen et al., 2021).

The different status and role of agriculture in different regions will affect the dissemination of information and technology applications, which may influence agricultural carbon emissions. Moreover, the emission decision of a region is influenced not only by its own agricultural resource and economic development level, but also by the emission decision of other regions (He et al., 2021). At the same time, the "Matthew effect" in the spatial network is relatively common. The regions occupying the central position of the network can often obtain numerous of resources by virtue of their location advantages, promoting carbon emissions reduction. Marginal regions exhibit minimal network benefit effect (He et al., 2021; Yang N. Z. et al., 2022; Song et al., 2022), which may further increase the gap between the impact of regional centres on agricultural carbon emissions and exacerbate the unbalanced development of agricultural carbon emissions. At present, there is no research on the effect of centrality on agricultural carbon emissions and its moderating effect between technological progress and agricultural carbon emissions based on agricultural social network associations. Under the background of deepening spatial correlation, it is necessary to deeply explore the relationship between centrality and agricultural carbon emissions based on SNA theory, reveal the influencing mechanism of spatial connection on agricultural carbon emissions, and provide practical reference for achieving China's carbon peak and neutral goals and the Sustainable Development Goals (SDGs) of the United Nations' Agenda 2030.

Based on the above analysis, the provincial panel data from 2001 to 2019 are used to quantitatively calculate agricultural carbon emissions and the SBM model is used to calculate and decompose agricultural technological progress. The agricultural centrality is calculated based on SNA theory and gravity model. Then the technological progress and agricultural network centrality are introduced into the impact analysis framework of agricultural carbon emissions from the perspective of spatial correlation. The GTWR model is used to reveal the spatiotemporal heterogeneity of agricultural carbon emissions in different regions based on different levels of technological progress and centrality. The moderating effect of agricultural centrality on technological progress and agricultural carbon emissions is further explored. Finally, we propose targeted policy suggestions based on the research findings to achieve the precise implementation of agricultural carbon emissions reduction.

The innovations of this paper are as follows. First, based on the perspective of SNA, this paper introduce the agricultural network centrality into the analysis framework of agricultural carbon emissions, study the impact of agricultural network centrality on agricultural carbon emissions and further explore its moderating effect on the relationship between technological progress and agricultural carbon emissions. These studies broaden the research perspective and improves the mechanism analysis. Second, the GTWR model is used to explore the impact of technological progress on the spatiotemporal heterogeneity of agricultural carbon emissions at different time in different regions. The conclusion is more accurate. Third, we identify the status and role of different regions in the social network of agricultural carbon emissions, which helps to explain the impact of technological progress on agricultural carbon emission reduction from the perspective of centrality. This could also provide ideas for building regional synergistic emission reduction mechanisms to achieve China's carbon emission goals.

2 Methods and data sources

2.1 Research methods

2.1.1 Calculation of agricultural carbon emissions

Carbon emissions in agriculture are mainly generated by chemical fertilizers, agricultural films, pesticides and agricultural machinery diesel used in agricultural production activities. Referencing the carbon sources and emissions coefficients of related researches (Tian et al., 2014; Liu D. D. et al., 2021; Yang H. et al., 2022), which mainly include pesticides 4.9341 kg/kg, agricultural films 5.18 kg/kg, chemical fertilizer 0.8956 kg/kg, agricultural diesel 0.5927 kg/kg, agricultural ploughing 312.6 kg/km^2 and agricultural irrigation 20.476 kg/hm^2. The calculation formula is as follows.

$$C = \Sigma C_i = K_i E_i \tag{1}$$

where C represents the total amount of agricultural carbon emissions, C_i denotes the i_{th} type of carbon emissions, K_i represents the use of the i_{th} carbon source, and E_i represents the carbon emission coefficient of the i_{th} carbon source.

2.1.2 Super-efficiency SBM model

The level of agricultural technological progress is estimated using the super-efficiency SBM model of undesired output. Referencing the existing research (Kuang et al., 2020; Liu D. D. et al., 2021; Xie et al., 2021), we first calculated the total factor productivity (TFP) of agriculture, in which the input is based on the different factors in the agricultural production process, including land, manpower, machinery, water, fertilizer, pesticide input, agricultural film and energy. Output indicators consist of expected and undesired output, wherein the expected output is the total agricultural output value, and the undesired output is the agricultural carbon emissions. Table 1 presents the variables and descriptive statistics. According to the Malmquist index, TFP of agriculture was cumulatively transformed to obtain the level of technological progress (Liu and Yang, 2021). The relevant calculation formula is as follows:

$$min\,\rho = \frac{\frac{1}{m}\sum_{i=1}^{m}\left(\bar{x}/x_{ik}\right)}{\frac{1}{h_1+h_2}\left(\sum_{p=1}^{h_1}\overline{y^d}\Big/y_{pk}^d + \sum_{q=1}^{h_2}\overline{y^u}\Big/y_{qk}^u\right)}$$

$$\begin{cases} \bar{x} \geq \sum\limits_{j=1,\neq k}^{n} x_{ij}\lambda_j;\ \overline{y^d} \leq \sum\limits_{j=1,\neq k}^{n} y_{pj}^d\lambda_j;\ \overline{y^u} \geq \sum\limits_{j=1,\neq k}^{n} y_{qj}^u\lambda_j \\ \bar{x} \geq x_k;\ \overline{y^d} \leq y_k^d;\ \overline{y^u} \geq y_k^u \\ \lambda_j \geq 0, i = 1, 2, \ldots m;\ j = 1, 2, \ldots n,\ j \neq 0 \\ p = 1, 2, \ldots h_1;\ q = 1, 2, \ldots h_2 \end{cases} \tag{2}$$

where n represents the number of decentralized management unit in the decision-making unit, m is the number of inputs, h_1 and h_2 represent the number of expected output and unexpected output, respectively. $\bar{x}$, $\overline{y^d}$ and $\overline{y^u}$ are the slack of input, expected output and unexpected output, respectively. x, y^d and y^u are the elements in the corresponding input matrix, expected output matrix and unexpected output matrix, respectively. ρ indicates the agricultural TFP value.

TABLE 1 Variable definitions and descriptive statistics.

Index	Variable category	Variable	Description	Mean	Standard deviation	Minimum	Maximum
Input	Land input	Crop sown area/10^3hm^2	Reflect the cultivated area Kuang et al. (2020)	5,147	3,737	89	14,903
	Human input	Number of employees in agriculture/10^4people	Number of agricultural labor force Yang H. et al. (2022)	957	720	37	3,478
	Mechanical input	Total power of agricultural machinery/10^4kW	Agricultural machinery is an important tool for agricultural production process Rehman et al. (2022)	2,785	2,704	94	13,353
	Water input	Effective irrigation area/ 10^3hm^2	Water consumption represented by effective irrigation area in agriculture Benbi (2018)	1,958	1,532	88	6,178
	Fertilizer input	Net amount of agricultural chemical fertilizer application/10^4t	Main pollution sources in agricultural production process Bhattacharyya et al. (2012)	172	140	3.020	716
	Pesticide input	Pesticide usage/10^4t	Main pollution sources in agricultural production process Rehman et al. (2022)	5.150	4.273	0.060	17.350
	Film input	Usage of agricultural film/ 10^4t	Main pollution sources in agricultural production process Yang H. et al. (2022)	6.862	6.411	0.0294	34.35
	Energy input	Agricultural diesel consumption/10^4t	Main pollution sources in agricultural production process Tian et al. (2014)	62.73	65.27	0.470	487.0
Expected output	Agricultural output	Total agricultural output value/10^8 CNY (China Yuan)	Converted to the constant price in 2001 to eliminate the impact of price changes Liu Z. et al. (2021)	2,282	2,033	52.78	9,672
Undesired output	Carbon emissions	Agricultural carbon emissions/10^4t		251.9	191.9	3.439	857.2

$$MI = EC * TC \tag{3}$$

$$TC = \sqrt{\frac{E^t(x^t, y^t)}{E^{t+1}(x^t, y^t)} \frac{E^t(x^{t+1}, y^{t+1})}{E^{t+1}(x^{t+1}, y^{t+1})}} \tag{4}$$

where MI represents the productivity index, EC is the change of technical efficiency in the two periods, TC is the change of production technology progress in the two periods. $E^t(x^t, y^t)$ and $E^{t+1}(x^{t+1}, y^{t+1})$ represent the technical efficiency value of region i in two periods. The technological progress is extracted referencing the method of Färe et al. and Yang et al. (Färe et al., 1992; Yang H. et al., 2022)

2.1.3 Social network analysis

SNA is one of the most widely used research methods in sociology and economics in recent years. The theoretical perspective of SNA focuses on the relationships and social structures between social actors. The object of SNA is a network structure consisting of the internal links of different actors. A network of inter-provincial agricultural production spatial linkages is constructed by calculating inter-regional gravity values. Through social network analysis, different agricultural centrality in each region are calculated to further explore the mechanisms of influence on agricultural carbon emissions.

2.1.3.1 Gravity model

The gravity model is introduced into the agricultural social correlation network, and the output value of agricultural in each region was divided by the square of the regional distance to reflect the agricultural spatial correlation between regions. The larger the agricultural output value and the closer the geographical distance between regions, the larger the gravitational value and the stronger the association. The greater the association between regions, the greater the mutual influence. The gravity value is converted into a gravity matrix (Shen et al., 2021). The calculation formula of the gravity value is as follows:

$$F_{ij} = kQ_iQ_j / D_{ij}^2 \tag{5}$$

where F_{ij} refers to the agricultural gravity value between regions i and j; Q_i, Q_j represent the total output value in agriculture in regions i and j, respectively. k is the gravity coefficient, usually taken as 1. D_{ij} represents the distance between the centres in regions i and j, which is measured by longitude and latitude. The formula indicates that the agricultural spatial correlation between regions is positively related to its scale and inversely related to the distance between regions. Agriculture is highly dependent on natural endowments. Due to similar natural resource endowments, climate and terrain conditions in adjacent areas, it is reasonable for us to choose geographical distance.

2.1.3.2 Network characteristics

With reference to relevant literature, we use network analysis indicators to quantify the different connectivity characteristics of each Chinese province, calculating the degree centrality and betweenness centrality of agricultural in each area (He et al., 2021; Shen et al., 2021). The degree centrality represents the ratio of the number of members directly associated with a member to the total number of individuals most likely to be directly associated. The higher the degree centrality, the more control a member has over other members. The betweenness centrality indicates the extent to which members of the network play a mediating role for other members. The higher the degree of betweenness centrality, the more pronounced the intermediary position of a member in the network. The degree centrality and betweenness centrality are used to characterise the different agricultural positions and roles of individual provinces, and to further explore the mechanisms of their influence on agricultural carbon emissions.

In the analysis of the overall network of agricultural links in China, all provinces are considered as the overall network structure and each province is considered as a node in the network. The connections between the regions are considered as edges in the network. The inter-provincial network of spatial linkages in agricultural production is based on a gravity model. The agricultural situation in each province is analysed by calculating the degree of agricultural centrality of each region, and the links between different provinces are explored through a social network linkage map.

2.1.4 Spatial autocorrelation

According to the first law of geography, "all things are related, but nearby things are more related than distant things" (Tobler, 1970), therefore, spatial correlation in terms of agricultural carbon emissions may also be present. Whether the spatial effect should be considered in the model depends on whether agricultural carbon emissions are geographically dependent and correlated. Moran's I (Moran, 1950) is used to test whether there is a spatial correlation in provincial agricultural carbon emissions. The Moran's I is calculated as follows:

$$I = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n} W_{i,j}(x_i-\bar{x})(x_j-\bar{x})}{\sum_{i=1}^{n}\sum_{j=1}^{n} W_{i,j}\sum_{i=1}^{n}(x_i-\bar{x})^2},\ i \neq j \tag{6}$$

where I represents the global Moran's I, n is the number of research units, and x_i and x_j are the agricultural carbon emissions in province i and j, respectively. $\bar{x}$ represents the average agricultural carbon emissions in each province, and W is the weight matrix of the spatial correlation between provinces i and j. The value of global Moran's I ranges from −1 to 1. If $I > 0$, there is a positive spatial correlation; conversely, if $I < 0$, it indicates a negative spatial correlation. If the absolute value is close to 0, it means the spatial distribution is random (Shen et al., 2021).

2.1.5 GTWR model

In contrast to traditional geographically weighted regression model that only consider spatial dimensions, the GTWR model combines both time and space factors. Incorporating the time dimension into geographic space to form a three-dimensional spatiotemporal weight matrix reveals the spatiotemporal evolution of the driving force of agricultural carbon emissions in each region at a certain period, which provides an analytical basis for simultaneously dealing with the "space-time" non-stationarity (Yang et al., 2021). The formula is as follows:

$$\begin{aligned} C = {} & \beta_0(u_i,v_i,t_i) + \beta_1(u_i,v_i,t_i)T_i + \beta_2(u_i,v_i,t_i)D_i \\ & + \beta_k(u_i,v_i,t_i)Cont_i + \varepsilon_i, \\ k = {} & 3, 4, \ldots, 8 \end{aligned} \tag{7}$$

where C represents the agricultural carbon emissions in each province. u_i, v_i, t_i represent the latitude, longitude and year of the i th region, respectively, representing the spatiotemporal coordinates of the i th region. $\beta_0(u_i,v_i,t_i)$ represents the space-time intercept term of region i. T_i represents the observed value of technological progress in region i, and β_1 is the estimated coefficient of technological progress. D_i represents the observed value of the centrality in region i, and β_2 is the estimated coefficient of centrality. $Cont_i$ denotes the remaining control variables, and β_k represents the estimated coefficient of control variables. ε_i is the model residual term.

Among them, the calculation formula of the observation point i at each spatiotemporal position and the estimated value of the k th independent variable is as follows:

$$\hat{\beta}(u_i,v_i,t_i) = [X^T W(u_i,v_i,t_i)X]^{-1} X^T W(u_i,v_i,t_i)Y \tag{8}$$

where $\hat{\beta}(u_i,v_i,t_i)$ represents the estimated coefficients of explanatory variables. $W(u_i,v_i,t_i)$ is the spatiotemporal weight matrix and is determined by the finite Gaussian function. X represents the independent variable matrix, and X^T is the transpose of the independent variable matrix. Y is the dependent variable agricultural carbon emission matrix.

The explained variable in the regression model is agricultural carbon emissions. An index system affecting China's agricultural carbon emissions is established based on the relevant research (Chen Y. H. et al., 2019; Liu D. D. et al., 2021; He et al., 2021; Koondhar et al., 2021; Sun and Xu, 2022). The related variables are shown in Table 2.

TABLE 2 Variable definitions and descriptive statistics.

Variable category	Variable/unit	Description	Mean	Standard deviation	Minimum	Maximum
Explained variable	Agricultural carbon emission (C)/10^4t	Based on carbon emission calculation formula	251	191	3.439	857
Core explanatory variables	Agricultural technological progress (TC)	Based on MI index decomposition	1.149	0.172	0.477	2.264
	Agricultural network centrality location centrality (DEG)	Calculated based on the gravity model	22,367	42,508	1.170	256,222
	betweenness centrality (BET)		5.958	6.852	0.015	25.510
Control variable	Number of labor (NEPI)/people	Employees in the primary industry	957	720	37.090	3,478
	Human capital (AYE)/year	Average years of education	8.492	1.251	3.430	12.780
	Industrial structure (PIO)	Proportion of secondary and tertiary industries	0.796	0.103	0.439	0.993
	Rural economic development level (GDPP)/10^4 CNY	Per capita net income of rural residents	3.400	2.662	0.300	16.456
	Level of financial support for agriculture (FSA)/10^4 CNY	Financial expenditure on agriculture, forestry, water affairs and policy subsidies	297	277	6.285	1,311
	Effective irrigation level of cultivated land (EIL)	Ratio of effective irrigation area to total sown area of crops	0.431	0.195	0.142	0.989

Core explanatory variables: 1) Agricultural technology progress. Relevant studies have shown that industrial technological progress can inhibit industrial carbon emissions (Chen et al., 2020; Zhang et al., 2020). In the field of agricultural production, the diffusion, learning and competition effect of agricultural technological progress among regions will affect agricultural carbon emissions (Yang et al., 2021). Through the decomposition of TFP, we can obtain the level of technological progress, and further explore the spatiotemporal heterogeneity of technological progress on agricultural carbon emissions (Xie et al., 2021; You and Zhang, 2022). 2) Agricultural network centrality. As the basic industry for human survival, agriculture not only has symbiotic characteristics caused by geographical location and climate environment, but also has spatial correlation behaviours such as imitation or competition caused by industrial homogeneity. The importance of different agricultural locations and different degrees of intermediary connection in the national agricultural social network may have a heterogeneous impact on regional agricultural carbon emissions (He et al., 2021). We calculate the agricultural point centrality and betweenness centrality according to the gravity model. The point degree of centrality reflects the provinces' position in the centre of China's agricultural social network. The larger the index value, the greater the regional centrality and the closer the relationship with other regions. For convenience of understanding, we use the location centrality in the interpretation of this paper. The betweenness centrality reflects regions' the intermediary role in agriculture. The greater the value, the greater the intermediary role of the region in the agriculture spatial social network (Al-Ezzi et al., 2021), so as to explore the impact of each province's agricultural status and the degree of intermediate contact on regional agricultural carbon emissions.

Control variables: 1) Employees in agriculture. Labour is one of the necessary factors for agricultural production activities. The use of agricultural machinery and the collection and use of agricultural information require labour input. Some studies demonstrate that higher employee investment leads to lower agricultural carbon emissions and higher ecological efficiency (Cui et al., 2018). 2) Human capital. The number of agricultural employees only accounts for changes in the number of agricultural labour, whereas human capital can provide relevant information regarding the quality of workers (Long et al., 2018). Human capital is measured by the average level of education. The level of education in each region represents the overall quality of the region, which also includes the quality of the labour force. Therefore, it is reasonable to use the average years of schooling of the population in each province as an approximate indicator of the level of human capital, referencing the research of Romer (1990) and Mankiw et al. (1992). 3) Industrial structure. The upgrading of industrial structure from the primary industry to secondary and tertiary industry has generated a squeeze on agriculture, resulting in the reduction of agricultural production activities and subsequent reductions in agricultural carbon emissions. The impact of the industries structure of

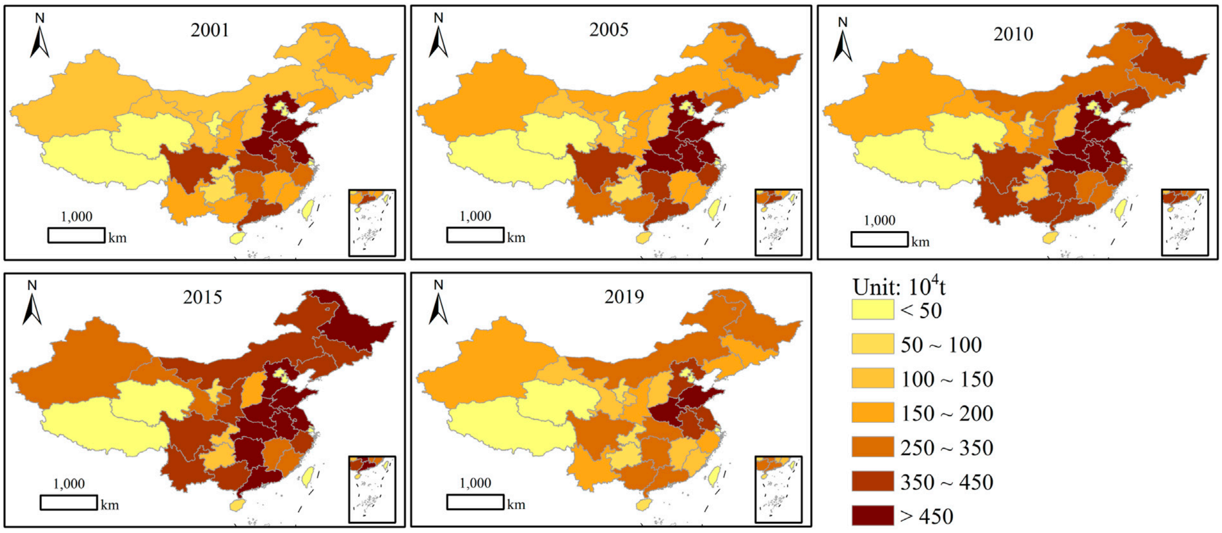

FIGURE 1
Agricultural carbon emissions by province (2001, 2005, 2010, 2015 and 2019).

agriculture is represented by the change in the proportion of secondary and tertiary output value on agricultural carbon emissions (He et al., 2021). 4) The level of rural economic development (Zhang et al., 2019). It is measured by rural per capita GDP. 5) The level of financial support for agriculture. The higher the value, the higher the government attaches importance to agriculture (Chavas, 2001; Guo et al., 2022). It is measured by the total of both financial expenditure on agriculture, forestry and water affairs as well as policy subsidies. 6) Effective irrigation level. It represents the effective use of water resources in agricultural production activities and is represented by the ratio of effective irrigation area to total sown crop area (Chen Y. H. et al., 2019). The variables involving prices are converted to the constant price in 2001 to eliminate the impact of price changes. The variables and descriptive statistics are shown in Table 2.

2.2 Data sources

The relevant data of 31 provinces (excluding Hong Kong SAR, China, Macao SAR, China and Taiwan) in China used in this paper are mainly from China Statistical Yearbook from 2001 to 2019 (http://www.stats.gov.cn/tjsj/ndsj/). The data of employees in primary industry are from China demographic and Employment Statistical Yearbook (http://www.stats.gov.cn/tjsj/). Some missing data comes from provincial statistical yearbooks (e.g., http://tjj.xinjiang.gov.cn/), and some missing data in individual years are processed using linear interpolation. The geographic longitude and latitude data are obtained from the Basic Geographic Information Centre in China (https://www.ngcc.cn/ngcc/).

3 Results

3.1 Temporal and spatial changes of agricultural carbon emissions

Due to the different natural resources and economic development levels of each province, there are considerable differences in agricultural carbon emissions. Figure 1 presents the agricultural carbon emissions of each province in 2001, 2005, 2010, 2015 and 2019. From the perspective of time sequence change, China's agricultural carbon emission shows a general trend of growth followed by decline. From 2001 to 2015, the vast majority of areas saw a significant increase in carbon emissions, especially in Henan, Inner Mongolia, Heilongjiang, Yunnan, Hebei, Jilin, Gansu, Guangxi, Anhui, Shaanxi, Hunan, Hubei, and Guangdong, where the increase in their carbon emissions was more than one million tonnes. From 2015 to 2019, most provinces achieved varying degrees of reduction in agricultural carbon emissions. Among them, Hebei, Shandong, Hubei, Henan, Yunnan, Gansu, Heilongjiang, Anhui and Jiangxi had very significant reductions of more than 400,000 tonnes in 4 years (Henan and Shandong remained in the highest classification after the reduction due to their large carbon emission base). This is probably because the Chinese government has become more and more explicit about carbon emission reduction in recent

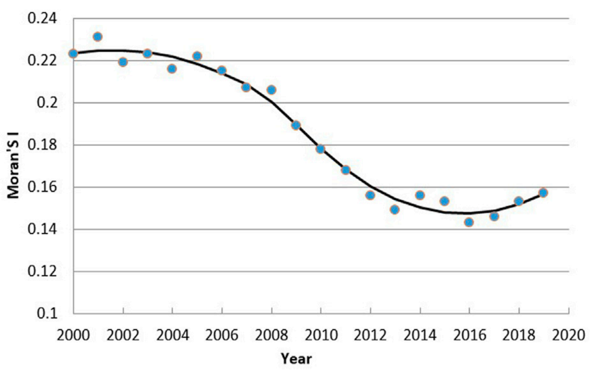

FIGURE 2
The changing trend of Moran's I of agricultural carbon emissions in China.

years, and all regions (especially the main grain-producing regions) have responded positively to the government's call for carbon emission reduction, which has had a significant effect.

From the perspective of spatial distribution, the characteristics of spatial agglomeration are significant, and primarily concentrated in major grain producing provinces in central and eastern China. Areas with high agricultural carbon emissions include Henan, Shandong, Hebei, Jiangsu, Anhui, Hubei, Heilongjiang, Hunan and other regions, all of which are major grain producing areas. Due to more input in agricultural production factors (fertilizers, pesticides, etc.), the carbon emissions are high in these provinces. The areas with low agricultural carbon emissions include Hainan, Ningxia, Shanghai, Tianjin, Qinghai, Beijing and Tibet etc., most of which are developed or remote regions. The industries in developed areas are concentrated in manufacturing and service industries, and the agricultural industry only accounts for a small proportion, therefore, agriculture produces less carbon emissions. In remote areas, due to natural climatic conditions and extensive operations, the pollution to the environment is relatively minimal, and the carbon emissions are relatively low.

3.2 Spatial autocorrelation analysis

To test whether the spatial effects should be considered in the regression, a global Moran autocorrelation test was performed on China's agricultural carbon emissions, and the results are shown in Figure 2. During the study period, the global Moran's I was greater than 0 and the Z value was greater than 1.65, which was significant at the 5% level. The overall Moran's I exhibited a downward trend first, followed by an upward trend. From 2001 to 2009, the global Moran's I was greater than 0.2. It began to decline in 2009 and then increased in recent years, indicating that the spatial autocorrelation and spatial agglomeration among provinces have increased in recent years. The results demonstrated a remarkable spatial autocorrelation in agricultural carbon emissions between provinces. Agricultural carbon emissions in a certain region have spatial spillover effects on other provinces, therefore, spatial effects should be considered when exploring the driving factors of China's agricultural carbon emissions.

3.3 Social network analysis

Network structure characterization and centrality analysis were used to determine the importance of each node in the agricultural carbon emission side of the network. The gravity model is used to calculate the location centrality and betweenness centrality of agricultural carbon emissions in each province. This provides a regional reference for subsequent policy formulation according to local conditions. The structure of social network connections in 2001 and 2019 are shown in Figure 3, where each node represents each province and a straight line connection means that there is a link between two provinces.

Figure 3 shows the network of agricultural connectivity for each province (node) in 2001 and 2019 respectively. From Figure 3, we can see how each province is connected to the other provinces. In both 2001 and 2019, the network is dominated by Henan, Shandong, Hubei, Jiangsu, Jiangxi, Zhejiang, and Anhui. These provinces always play an important role in the spatially linked network of agricultural carbon emissions in China. Provinces with significantly increased connectivity and importance to other regions in the connectivity network mainly include Inner Mongolia, Sichuan, Hunan, Shaanxi, and Guizhou. These provinces are increasingly important in the China's agriculture and are more likely to have an impact on other regions. Provinces with significantly lower connectivity to other regions in the connectivity network include Beijing, Tianjin, and Tibet. Due to economic development or remote geographical location, these regions are less important in the agricultural network and have less impact on other regions.

Due to space constraints in the paper, only the location centrality and the betweenness centrality of 2019 are shown in Tables 3, 4. The location centrality and the betweenness centrality are both reported the normalized result. Table 3 shows the location centrality results. The regions with high level of location centrality include Henan, Shandong, Hubei, Jiangsu, Jiangxi, and Zhejiang, followed by Inner Mongolia, Anhui, Fujian, Sichuan, Shanghai, Hunan, and Hebei. Most of the above-mentioned provinces are large agricultural provinces in the north or in the middle and lower reaches

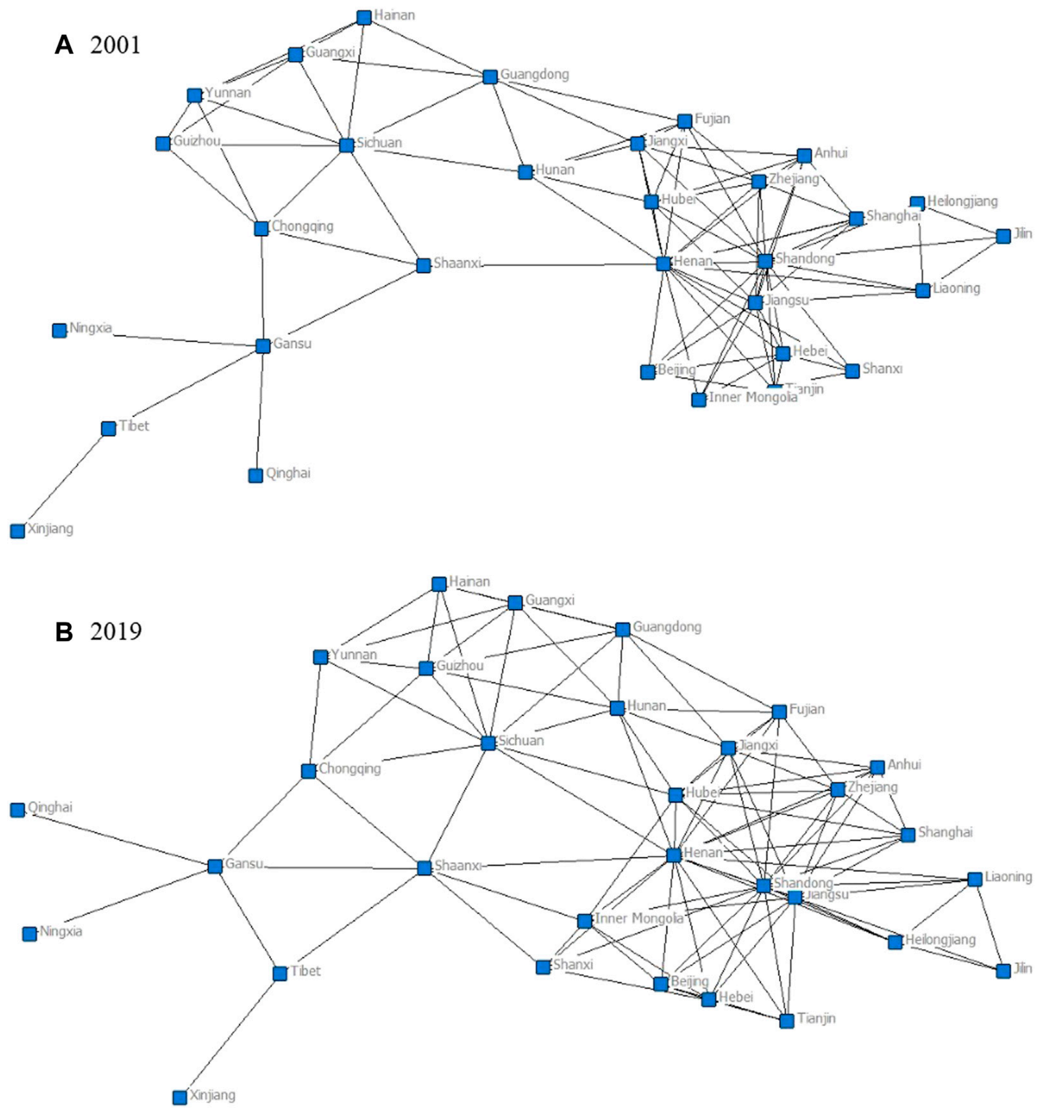

FIGURE 3
Social network structure based on centrality in China.

TABLE 3 Spatial distribution of location centrality.

Grade	Location centrality	Province
Highest	(2.633, 4.167)	Henan, Shandong, Hubei, Jiangsu, Jiangxi, Zhejiang
High	(2.133, 2.633)	Inner Mongolia, Anhui, Fujian, Sichuan, Shanghai, Hunan, Hebei
Medium	(1.567, 2.133)	Shanxi, Liaoning, Heilongjiang, Shaanxi, Beijing, Tianjin
Low	(0.933, 1.567)	Guangdong, Guizhou, Guangxi, Hainan, Chongqing, Yunnan
Lowest	(0.067, 0.933)	Jilin, Tibet, Gansu, Qinghai, Ningxia, Xinjiang

of the Yangtze River, which are relatively concentrated in the spatial correlation of agricultural carbon emissions in China. The findings indicate that the stability of the overall network structure is highly dependent on these provinces, which have a key role in the spatial pattern of China's agricultural carbon emissions. The provinces with low level of location centrality

TABLE 4 Spatial distribution of betweenness centrality.

Grade	Betweenness centrality	Province
Highest	(0.022, 0.200)	Henan, Shaanxi, Sichuan, Anhui, Hubei, Hunan
High	(0.008, 0.022)	Shanxi, Inner Mongolia, Shandong, Gansu, Jiangxi, Hebei
Medium	(0.002, 0.008)	Guangdong, Jiangsu, Zhejiang, Fujian, Guizhou, Chongqing, Yunnan
Low	(0.001, 0.002)	Beijing, Tianjin, Tibet, Liaoning, Heilongjiang, Shanghai
Lowest	(0, 0.001)	Guangxi, Hainan, Jilin, Qinghai, Ningxia, Xinjiang

include Guangdong, Guizhou, Guangxi, Hainan, Chongqing, Yunnan, and the regions with the lowest level of regional centrality include Jilin, Tibet, Gansu, Qinghai, Ningxia, and Xinjiang. Most of these areas are remote areas, where agricultural carbon emissions are less related to other provinces, leaving them in a subordinate position in the social correlation network of China's agricultural carbon emissions. Although Jilin is also one of the main agricultural producing areas, the remoteness of the region and its distance from the rest of China's provinces has resulted in a low centrality, which is less connected to other regions due to geographical distance, natural climate, etc. Similar to this are Heilongjiang and Liaoning.

Table 4 shows the betweenness centrality results. The provinces with the highest betweenness centrality include Henan, Shaanxi, Sichuan, Anhui, Hubei, and Hunan. Those with high degree of betweenness centrality include Shanxi, Inner Mongolia, Shandong, Gansu, Jiangxi, and Hebei. These provinces are in the core of the spatial network of agricultural and have a strong ability to control agricultural carbon emissions in other provinces. The provinces with low levels of betweenness centrality mainly include Beijing, Tianjin, Tibet, Liaoning, Heilongjiang, and Shanghai. The provinces with the lowest level of betweenness centrality are Guangxi, Hainan, Jilin, Qinghai, Ningxia, and Xinjiang. These regions are easer affected by those with high betweenness centrality, and it is difficult to control or dominate the carbon emissions in other regions.

In general, each province shows significant unbalanced characteristics in the social association network of agricultural, but many province shows relative consistency in the location centrality and betweenness centrality. Henan, Shandong, Hubei, Jiangxi, Jiangsu, Inner Mongolia, Anhui, Sichuan, Hunan, Hebei, and other cited regions, have high location centrality and betweenness centrality. Most of them are large agricultural provinces. They are in a significant central position in the associated network, with a strong intermediary and control role. In contrast, Guangxi, Hainan, Chongqing, Jilin, Tibet, Qinghai, Ningxia, Xinjiang, and other regions have low location centrality and betweenness centrality, and have a marginal position in the social networking.

3.4 Empirical model analysis

3.4.1 Correlation and collinearity analysis

To understand the correlation between variables and avoid collinearity, the Pearson correlation analysis and the variance inflation factor (VIF) test are performed on the variables involved. The results are shown in Tables 5, 6, respectively. Table 5 indicates the dependent variable has a high correlation with each independent variable, while the correlation between independent variables is low. The VIF test results are shown in Table 6. The VIF of each independent variable is less than 8, and the average VIF is 3.49, indicating that there is no serious collinearity between the independent variables. The next step of the regression analysis can be performed.

3.4.2 GTWR model

Table 7 presents the model fitting results of ordinary least squares (OLS), time weighted regression (TWR), geographically weighted regression (GWR) and GTWR. It can be seen that the R^2 increases significantly and AICc is smaller after adding spatial weight. Comprehensively comparing various indicators, the GTWR model is the most accurate, thus, the GTWR model is used for empirical analysis. ArcGIS 10.2 software is used to present the spatial pattern evolution trend of the core explanatory variables (technological progress, location centrality and betweenness centrality) on the influence coefficient of provincial agricultural carbon emissions. Due to space limitations, Figure 4 only presents 2000, 2010 and 2019.

In terms of technological progress, technological progress has a negative effect on agricultural carbon emissions, and the regression coefficient decreases from western to eastern regions. The spatial gradient distribution characteristics are obvious, with significant heterogeneity among provinces. In 2000, the regression coefficients of most provinces is negative, indicating that technological progress had an inhibitory impact on agricultural carbon emissions. Moreover, they mainly distributed in major grain areas. In 2010 and 2019, the regression coefficients of all provinces decreased significantly. In 2019, only three regions of Hainan, Guangxi and Tibet had

TABLE 5 Correlation test between variables.

Variable	C	TC	DEG	BET	NEPI	AYE	PIO	GDPP	FSA	EIL
C	1									
TC	−0.093**	1								
DEG	−0.501***	0.027	1							
BET	0.816***	−0.059	0.465*	1						
NEPI	0.050*	0.085**	0.219***	0.068*	1					
AYE	−0.163***	0.102**	0.224***	0.084**	0.478**	1				
PIO	−0.790***	−0.127***	0.266**	0.432**	−0.208**	−0.302***	1			
GDPP	−0.036*	0.164***	0.307***	0.096**	0.101***	0.365***	−0.293**	1		
FSA	0.461***	0.065	0.246*	0.398***	0.353***	0.218*	0.214***	0.362***	1	
EIL	−0.149***	0.164***	0.011	−0.041	0.148***	0.366***	−0.221*	0.410**	0.015	1

Notes: *, **, *** represent significance at 10%, 5% and 1%, respectively.

TABLE 6 VIF test of explanatory variables.

Variable	VIF	1/VIF
GDPP	7.69	0.13
BET	5.80	0.17
FSA	4.46	0.22
DEG	4.24	0.24
NEPI	3.37	0.30
AYE	2.44	0.41
PIO	2.11	0.47
EIL	1.79	0.56
TC	1.29	0.78
Mean VIF	3.49	

positive regression coefficients, and the remaining 28 provinces are all negative. The regression coefficient decreased significantly, and the number of provinces changed from positive to negative, indicating an increasingly inhibitory impact of technological progress on agricultural carbon emissions.

In terms of location centrality, the regression coefficients of most provinces in 3 years are negative, except for Hainan and Qinghai in 2001, Xinjiang, Qinghai and Gansu in 2010, and Yunnan, Qinghai, Chongqing, Shaanxi, Ningxia, Guangxi, Gansu, Hainan, and Guizhou in 2019. This indicates that the location centrality has a negative impact on agricultural carbon emissions, and the greater the agricultural location centrality of a region, the less the agricultural carbon emissions of the region.

In terms of betweenness centrality, the number of provinces with positive regression coefficients for betweenness centrality in 2001 and 2010 is 24 and 25, respectively. However, the regression coefficients of 15 provinces are negatively correlated in 2019. The number of regions whose regression coefficient changed from positive to negative has increased. The regression coefficient of most positive correlation provinces has decreased, and the positive correlation has weakened, indicating that the effect of mediation on agricultural carbon emissions had a trend from positive to negative.

3.4.3 Moderating effect

The fixed-effect hierarchical regression method is used to conduct empirical tests with referencing related studies to further explore the influencing mechanism of centrality on technological progress and agricultural carbon emissions (Verdier, 2020; Lv et al., 2021; Qi et al., 2021; Zheng et al., 2021).

First, we verify the moderating effect of the interaction term between technological progress and location centrality on agricultural carbon emissions. The first step is to conduct the regression of technological progress and agricultural carbon emissions. The second step is introducing the location centrality into the model as an independent variable for regression. The third step is adding the interaction term between technological progress and location centrality for regression. The results are shown in columns 1), 2) and 3) in Table 8, respectively. Column 1) reveals a significant negative effect between technological progress and agricultural carbon emissions, which is consistent with the results in Figure 4. Column 2) demonstrates that location centrality has a positive effect on agricultural carbon emissions. After introducing the interactive term of technological progress and location centrality in column 3), the location centrality shows a significant negative impact on agricultural carbon emissions, indicating that greater location centrality leads to more important the status and the less agricultural carbon emissions. The interaction coefficient is significantly negative ($\beta = -0.838$, $p < .01$), indicating the

TABLE 7 Model selection and regression results.

	OLS	GWR	TWR	GTWR
Bandwidth		0.115	0.196	0.115
Residual Squares	3.747	0.862	3.121	0.570
Sigma	0.081	0.038	0.073	0.031
AICc	−1283	−1992	−1342	−2121
R^2	0.874	0.971	0.895	0.981
R^2Adjusted	0.872	0.971	0.893	0.981
Trace of SMatrix		76.802	32.751	116.521
Spatiotemporal Distance Ratio				0.442

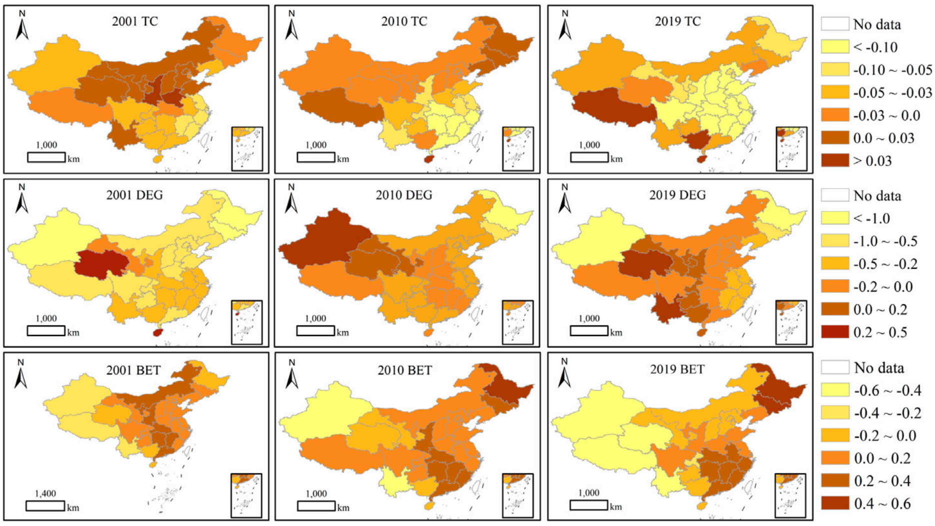

FIGURE 4
Spatiotemporal heterogeneity of the impact of technological progress and centrality on agricultural carbon emissions.

location centrality has a significant positive moderating effect on the relationship between technological progress and agricultural carbon emissions. The greater the regional agricultural location centrality is, the stronger the inhibition effect of technological progress on agricultural carbon emissions is. In contrast, the smaller location centrality leads to weaker the inhibition effect of technological progress on agricultural carbon emissions. Location centrality strengthens the negative impact of technological progress on agricultural carbon emissions.

Second, we verify the impact of the interaction term between technological progress and betweenness centrality on agricultural carbon emissions. The first step is performing the regression of technological progress and agricultural carbon emissions, the second step is introducing betweenness centrality into the model as an independent variable for regression, and the third step is adding the interaction term between technological progress and betweenness centrality for regression. The results are shown in columns (1), (4) and (5) in Table 8, respectively. In column (4), the overall effect of betweenness centrality on agricultural carbon emissions is positive, which is consistent with Figure 4. The interaction coefficient between technological progress and betweenness centrality in column (5) is significantly negative ($\beta = -0.479$, $p < .05$), indicating that betweenness centrality significantly strengthens the negative effect of technological progress on agricultural carbon emissions with a positive regulatory effect. The greater the regional betweenness centrality, the stronger the inhibitory impact of technological progress on agricultural carbon emissions; the smaller the betweenness centrality, the weaker the inhibitory impact of

TABLE 8 Regression results of moderating effect.

Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
TC	−0.122**	−0.101**	−0.137**	−0.066*	−0.129***	−0.068**	−0.089**	−0.114***
	(0.043)	(0.041)	(0.049)	(0.032)	(0.038)	(0.030)	(0.037)	(0.039)
DEG		0.311***	0.315***			−0.181***	−0.176***	−0.167***
		(0.041)	(0.030)			(0.029)	(0.033)	(0.036)
TC*DEG			−0.838***				−0.488**	
			(0.257)				(0.229)	
BET				0.371***	0.364***	0.442***	0.439***	0.431***
				(0.016)	(0.018)	(0.019)	(0.019)	(0.024)
TC*BET					−0.479**			−0.351*
					(0.223)			(0.180)
NEPI	0.814***	0.782***	0.783***	0.490***	0.486***	0.447***	0.449***	0.448***
	(0.032)	(0.029)	(0.029)	(0.021)	(0.020)	(0.019)	(0.020)	(0.020)
AYE	0.388***	0.411***	0.410***	0.349***	0.347***	0.328***	0.328***	0.329***
	(0.025)	(0.020)	(0.019)	(0.019)	(0.020)	(0.022)	(0.021)	(0.021)
PIO	−0.097***	−0.140***	−0.140***	−0.195***	−0.193***	−0.188***	−0.188***	−0.188***
	(0.024)	(0.036)	(0.036)	(0.032)	(0.032)	(0.031)	(0.032)	(0.032)
GDPP	−0.255***	−0.257***	−0.254***	−0.250***	−0.249***	−0.248***	−0.246***	−0.247***
	(0.032)	(0.032)	(0.032)	(0.031)	(0.030)	(0.032)	(0.031)	(0.031)
FSA	0.479***	0.290***	0.280***	0.307***	0.312***	0.384***	0.378***	0.382***
	(0.066)	(0.051)	(0.053)	(0.047)	(0.046)	(0.055)	(0.056)	(0.057)
EIL	0.325***	0.318***	0.314***	0.210***	0.204***	0.193***	0.191***	0.190***
	(0.019)	(0.018)	(0.019)	(0.012)	(0.013)	(0.013)	(0.013)	(0.013)
C	−0.179***	−0.145***	−0.128***	−0.0446**	−0.0192	−0.0390**	−0.0298*	−0.0208
	(0.025)	(0.031)	(0.028)	(0.018)	(0.020)	(0.017)	(0.014)	(0.017)
Observations	589	589	589	589	589	589	589	589
R^2	0.788	0.809	0.811	0.875	0.877	0.879	0.880	0.880

Notes: *, **, *** represent significance at 10%, 5% and 1%, respectively.

technological progress on agricultural carbon emissions. Although the betweenness centrality has a positive effect on agricultural carbon emissions overall, it can significantly strengthen the inhibitory effect of technological progress on agricultural carbon emissions. It may be that regions in the middle of the communication between nodes have a significant role as a bridge and a strong ability to control resources. It is easier to grasp the advantages of various information, technology and other resources over time in these regions, resulting low-carbon and carbon reduction in agriculture.

Finally, in order to ensure the robustness of the moderating effect, location centrality and betweenness centrality are introduced in column (6), and the interactive terms of technological progress and location centrality and the interactive terms of technological progress and intermediary centrality are introduced in columns (7) and (8), respectively. The interaction term between technological progress and centrality is tested by regression. The results are shown in columns (6), (7) and (8) in Table 8, respectively. The coefficients of the interaction terms are all significantly negative, indicating that location centrality and betweenness centrality both have a significant positive moderating effect on the relationship between technological progress and agricultural carbon emissions. With the increase of location centrality and betweenness centrality, the impact of technological progress on agricultural carbon emissions increases. The sign and significance of the regressions in columns (3) and (6) are relatively consistent with columns (7) and (8), respectively, indicating that the regression results are robust.

4 Discussion

4.1 Theoretical mechanism analysis

According to the first law of geography "all things are related, but nearby things are more related than distant things" (Tobler, 1970). Similarly, agriculture interact with each other in different regions, and carbon emissions are linked in different regions. The social network association uses a gravity model that takes into account the distance between two regions and the agricultural situation to measure the relationship and status of subjects in different regions. In this paper, social network analysis is used to obtain the locational centrality and betweenness centrality of agriculture, and to explore the mechanisms by which different locational centrality plays a role in agricultural carbon emissions.

The increase or decrease of agricultural carbon emissions in one region will adjust its own emissions according to the reference of other regions. This cooperative approach to emissions reduction can be explained by the "peer effect". The emission decision of a region is influenced not only by its own agricultural resource and economic development level, but also by the emission decision of other regions (He et al., 2021).

As an important way to achieve emission reduction, technological progress has become an important direction of mutual learning among regions. Through the "learning effect", agricultural technology progress may benefit more regions in emission reduction (Xie et al., 2021). The different status and role of agriculture in different regions will influence the voice of agriculture in China, and further influence the dissemination and application of technology, which in turn will have a certain impact on agricultural carbon emissions. In addition, due to the "Matthew effect", regions that occupy the centre of the network can obtain a large amount of resources and promote their own carbon emission reduction by virtue of their location, which further intensifies the unbalanced development of carbon emissions in agricultural regions with different centres.

The analysis of spatial heterogeneity and moderating effect helps to explain the impact of technological progress on agricultural carbon emissions from the perspective of centrality. We can understand the impact mechanism of agricultural status and role on regional government decision-making better, and these provide ideas for the construction of regional collaborative emissions reduction mechanism. The specific impact mechanisms are analysed below.

First, the agricultural status and role of different provinces are explored. Each province shows significant unbalanced characteristics in the social association network of agricultural carbon emissions, but the same provinces have relative consistency in the location centrality and betweenness centrality. The provinces with high location centrality and betweenness centrality are in a significant central position in the associated network, have a strong intermediary and control role. The provinces with low location centrality and betweenness centrality are in a marginal position in the social network. Different degrees of centrality result in different levels of impact on other areas in the network of agricultural carbon connections.

Second, the research found that the technological progress has a negative effect on agricultural carbon emissions. Since technological progress is confirmed to reduce agricultural carbon emissions by improving agricultural machinery and other processes, with a strong positive externality. The location centrality has a negative impact on agricultural carbon emissions. The greater a region's agricultural location centrality, the lower the region's the agricultural carbon emissions. It may be that the area is more connected to other areas in the social network and that learning behaviours occur to adopt measures to reduce agricultural carbon emissions. The increase of the regression coefficient from negative to positive indicates that the carbon reduction bonus brought by the agricultural location centrality has reduced, and the progress of science and technology and the convenience of information dissemination lead to a reduction in the network connectivity advantage of the location centrality. The effect of betweenness centrality on agricultural carbon emissions had trend from positive to negative. These enlighten the government to attach importance to the technology and the intermediary advantages of the region to grasp resources and actively learn and exchange to reduce agricultural carbon emissions.

Third, the moderating effect of agricultural centrality on the relationship between technological progress and agricultural carbon emissions is explored. The agricultural location centrality and betweenness centrality have a significant positive moderating effect on the relationship between technological progress and agricultural carbon emissions. With the increase of location centrality and betweenness centrality, the inhibitory effect of technological progress on agricultural carbon emissions increases. This is probably due to the fact that the higher the centrality of a region, the stronger the lead and diffusion role it plays, allowing for faster and wider diffusion of technology. Due to the centrality advantage, more resources such as information and technology can be obtained, thus curbing agricultural carbon emissions. Therefore, the moderating effect of high centrality on technological progress and agricultural carbon emissions should also be emphasized, and inhibition effect of technological progress on agricultural carbon emissions should be strengthened to achieve more efficient carbon reduction.

4.2 Policy implications

Based on the above analysis of carbon emissions, agricultural centrality and the regulation effect of centrality on carbon emissions in different regions, the status and role of different agricultural centrality regions are discussed from the perspective of carbon emission reduction, and corresponding suggestions are put forward to reduce agricultural carbon emissions and help achieve the SDGs.

1) The advantages of agricultural regional centres should be valued, and the driving and diffusion effects should be enhanced. For Henan, Shandong, Hubei, Jiangxi, Jiangsu, Inner Mongolia, Anhui, Sichuan, Hunan, Hebei, the major agricultural carbon emission provinces are also regions with high location centrality, and they have a key driving role in the spatial pattern of China's agricultural carbon emissions. Areas such as Henan, Shaanxi, Sichuan, Anhui, Hubei, Hunan, Shanxi, Inner Mongolia, Shandong, Gansu, Jiangxi and Hebei have a high betweenness centrality and play the role of a bridge of communication. It is important to give full play to the advantages of agricultural regional centres to enhance the driving and diffusion effects. Therefore, it is necessary to consider the moderating effect of spatial correlation effects on carbon emission reduction. Since regions with higher centrality are easer connected with other regions and have more significant carbon emissions reduction effects, policy formulation should take advantage of the special status of such regions, make full use of the diffusion effect of such regions, and actively promote low-carbon production technologies and effective policies to facilitate agricultural carbon emission reduction in other regions.
2) Policy guidance and financial support for marginalised agricultural areas should be strengthened. For agricultural regions with low locational centrality and marginalised in socially connected networks, such as Guangxi, Hainan, Chongqing, Jilin, Tibet, Qinghai, Ningxia, Xinjiang and other regions (provinces with essentially no agricultural industry are omitted), policy guidance should be strengthened and active learning from areas with significant agricultural carbon reduction.
3) The regional coordination mechanisms for emission reduction should be established, and regional exchanges and collaboration should be promoted and strengthened. There is an obvious spatial correlation between agricultural carbon emissions. The carbon emissions of a region are not only related to the agricultural and economic development of this region, but are also influenced by the relevant spatial social networks in the region, showing a learning behaviour of agricultural carbon emission reduction. Therefore, a regionally coordinated mechanism for emission reduction should be established so that regions can learn from each other to achieve sustainable development and ecological civilization in agriculture.
4) It is important to focus on the progress and application of agricultural science and technology, as well as the moderating role of the central degree on agricultural technology. On the one hand, agricultural economic linkages should be strengthened to clear obstacles to the spatial spillover of technological progress and allow different regions to benefit from technological progress. On the other hand, we should make full use of the moderating effect of high centrality on technological progress and agricultural carbon emissions, and strengthen the inhibiting effect of technological progress on agricultural carbon emissions to achieve higher and more efficient carbon emission reduction.

4.3 Limitations

Due to limited data availability, the primary sources of agricultural carbon emissions considered in this research include six common categories, including pesticides, agricultural films, agricultural irrigation, chemical fertilizer, agricultural ploughing, and agricultural diesel. Theoretically, the crop type and different farming methods also have impact on carbon emissions, which may affect the results. Therefore, further research should performed in future. In addition, agricultural carbon emissions may influenced by many factors at different spatial and temporal scales. We selected only some of potential variables, but the influence of residents' environmental awareness, governmental policy priorities and other circumstances are important. It is required further exploration including these factors.

5 Conclusion

This study use relevant data from 31 provinces in China from 2001 to 2019 to explore the spatiotemporal changes of agricultural carbon emissions. The SBM model, SNA and GTWR model are used to study the effect of technological progress and agricultural centrality on the spatiotemporal heterogeneity of agricultural carbon emissions. The moderating effect of agricultural centrality on the relationship between technological progress and agricultural carbon emissions is further explored. The main conclusions are as follows.

First, agricultural carbon emissions in China increased significantly during the study period. The spatial agglomeration characteristics were significant, and they were mainly concentrated in major grain producing areas. There is a significant spatial dependence of agricultural carbon emissions among provinces. The non-equilibrium characteristics of each province in the social network of agricultural carbon emissions are noticeable, while the same provinces show relative consistency in terms of location centrality and betweenness centrality. Areas with high centrality are the major grain producing areas, and they invariably play an important role in the spatially linked network of agricultural carbon emissions.

Second, technological progress has an inhibitory effect on agricultural carbon emissions, and the inhibitory effect gradually increases. The regression coefficient decreases from western to eastern regions, with remarkable spatial gradient distribution characteristics. The agricultural location centrality has a negative effect on overall agricultural carbon emissions, and the spatial heterogeneity is significant, however, the number of regions where the impact has changed from negative to positive has increased over time, indicating that the carbon reduction dividend brought by location centrality has decreased. The impact of betweenness centrality on agricultural carbon emissions has changed from positive to negative in many provinces over time. The enhancement of provinces' intermediary role has a trend of promoting the inhibiting impact on agricultural carbon emissions.

Third, agricultural location centrality and betweenness centrality have a significant positive moderating effect on the relationship between technological progress and agricultural carbon emissions. With the increase of location centrality and betweenness centrality, the inhibitory effect of technological progress on agricultural carbon emissions increases.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

HH performed concept development, modeling analysis, and writing. RD performed writing-review and editing. All authors contributed to the article and approved the submitted version.

Funding

This research is funded by the China National Key R&D Program (2022YFF0607404), Natural Science Foundation of China (42206240), Shandong Provincial Natural Science Foundation, China (ZR2020QD055).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 05 January 2023
DOI 10.3389/fenvs.2022.1064333

OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Environmental Economics and Management, a section of the journal Frontiers in Environmental Science

RECEIVED 08 October 2022
ACCEPTED 05 December 2022
PUBLISHED 05 January 2023

CITATION
Ma X, Xin B and Wu G (2023), Multi-agent game analysis on standardized discretion of environmental administrative penalty.
Front. Environ. Sci. 10:1064333.
doi: 10.3389/fenvs.2022.1064333

Multi-agent game analysis on standardized discretion of environmental administrative penalty

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An environmental administrative penalty is a powerful tool to regulate environmental pollution and ecological destruction by punishing intentional violations. Still, unchecked discretion may lead to excessively low or high penalties, breaking our balance of desire for uniformity with the need for discretion. To achieve the balance, regulators may use standardized discretion to achieve greater compliance by punishing intentional violations in a standardized way. However, policymakers and scholars have different attitudes on understanding whether standardized discretion helps enforcement. For this purpose, we construct a muti-agent dynamic game under the standardized discretion of environmental administrative penalty (SDEAP). The results show that: i) SDEAP can positively affect firms' output and emission reduction efforts but negatively affect environmental quality; ii) The lower limit of SDEAP can positively affect environmental quality but negatively affects firms' output and emission reduction efforts; iii) The upper limit of SDEAP can positively affect firms' output, emission reduction efforts, and environmental quality; iv) SDEAP can restrict law enforcement and improve firms' efforts to reduce emissions. This work can be helpful both to firms and the government as the basis for developing and implementing SDEAP.

KEYWORDS

multi-agent game, standardized discretion, environmental administrative penalty, dynamic equilibrium, green development

1 Introduction

Resources shortage and environmental pollution have long restricted the sustainable development of China's economy (Yu et al., 2020; Kong et al., 2021; Ma et al., 2022; Wang et al., 2022), which requires scientific and practical implementation of environmental regulation policies (Wang & Wang, 2022). However, in the process of environmental regulation, the phenomena that different penalties for the same or similar environmental

TABLE 1 Cases of environmental administrative penalties in Heze City in 2013[2].

Case	Firm	Violation	Penalty
1)	Shandong Ruiying Xianfeng Pharmaceutical Co., Ltd.	The concentration of SO_2 in the exhaust gas is 356 mg/m^3, 0.19 times higher than the emission standard value (300 mg/m^3)	20,000RMB
2)	Heze Huanyu Thermal Power Co., Ltd.	The concentration of SO_2 in the exhaust gas is 621 mg/m^3, 1.07 times higher than the emission standard value (300 mg/m^3)	50,000RMB
3)	Heze Lukang Sheryl Pharmaceutical Co., Ltd.	The concentration of SO_2 in the exhaust gas is 1270 mg/m^3, 2.23 times higher than the emission standard value (300 mg/m^3)	30,000RMB

TABLE 2 Cases of environmental administrative penalties in Weihai City in 2015[4].

Case	Firm	Violation	Penalty
4)	Weihai Weigao Real Estate Development Co., Ltd.	Construction noise at night	5,000RMB
5)	Weihai Yinpeng Construction Group Co., Ltd.		8,000RMB
6)	Weihai Jianfeng Construction Group Co., Ltd.		10,000RMB

violations often occur. It causes unfairness (Zhang et al., 2018; Sancho, 2021). Take the cases of Heze City and Weihai City in Shandong Province as examples.

Example 1. Some cases in Heze City in 2013 are shown in Table 1. Article 48 of Law of the People's Republic of China on the Prevention and Control of Air Pollution (2000[1]) stipulates that whoever discharges[2] pollutants into the atmosphere over the national and local discharge limits shall be fined 10,000–100,000 RMB.

Example 2. Some cases in Weihai City in 2015 are shown in Table 2. Article 56 of Law of the People's Republic of China on the Prevention and Control of Ambient Noise Pollution (1997[3]) stipulates that whoever produces night construction noise in an area where noise pollution is prohibited should be fined.

The penalties in these six cases are legal but unfair. In example 1, the penalty amount in Case 2) is much higher than that in Case 3), while the SO_2 concentration in Case 2) is lower than that in Case 3). In example 2, Cases (4–6) were penalized differently when they committed the same environmental violations. The broad penalty range gives law enforcers discretionary power. The misuse of discretion causes these unfair phenomena. Still, it is just the tip of the iceberg. Only in 2021, the Chinese government issued more than 55,200 decisions of environmental administrative penalties. The total amount of fines is up to 4.33 billion RMB. The number of cases and fines is enormous. If discretion is not well used, a lot of misuses occur.

Misuses of discretion may breed corruption and unfairness, causing an indelible negative impact. An insufficient penalty is not conducive to eco-environmental protection, while an excessive penalty is not conducive to economic development (Chang et al., 2020). Therefore, the appropriateness and standardization of discretion are crucial (Kochtcheeva, 2010). China took the lead in the standardized discretion of environmental administrative penalty (SDEAP). It is one of the rules specially set to regulate environmental administrative discretion. This regulation system is vital to change the misuse of discretion. Since 2009, the Ministry of Ecology and Environment of China has issued many policies, including the Guidance on Standardizing the Exercise of the Discretion of Environmental Supervision and Law Enforcement, the Reference Guide for Refining the Discretion of Administrative Penalty for Major Environmental Violations, and the Catalogue of Administrative Penalty of Environmental Protection Administration Set by Laws. In 2019, the Ministry of Ecology and Environment issued the Guiding Opinions on Further Standardizing the Discretion of Environmental Administrative Penalty. SDEAP has become a new tool widely used in China's environmental regulation.

SDEAP aims to solve the problems of broad discretion and misuse of discretion in environmental protection. To explain the SDEAP in further detail, we take the Law of the People's Republic of China on the Prevention and Control of Air Pollution as an example. The narrowest penalty range is 500–20,00 RMB. The

1 The administrative penalties in Table 1 were made according to the law of 2000. Now the law was supplemented and revised in 2015.

2 Data is obtained from the Ecological Environment Bureau of Heze city: http://hzsthj.heze.gov.cn/col/col66818/index.html?uid=88124&pageNum=48.

3 The administrative penalties in Table 2 were made according to the law of 1997. Now the law was supplemented and revised in 2022.

4 Data is obtained from Weihai Ecological Environment Bureau: http://sthj.weihai.gov.cn/col/col81006/index.html?uid=207606&pageNum=52.

10.3389/fenvs.2022.1064333

TABLE 3 Standardized discretion in article 48[6].

Indicator	Violation	Penalty amount (RMB)
Excess concentration of pollutants	0–100%	10,000–40,000
	100%–200%	40,000–60,000
	200%–300%	60,000–80,000
	Over 300%	80,000–100,000
	Extremely serious	100,000

most comprehensive penalty range is 100,000–1000,000 RMB. The upper limits of the penalties are 4–10 times the lower limits. The penalty range stipulated in the law is overbroad. SDEAP restricts discretion by refining the penalty range. As article 48[5], the standardized discretion is shown in Table 3[6].

Table 3 shows how the SDEAP restricts discretion. There are three vital elements in SDEAP: the intensity of standardized discretion and the lower and upper limits of the administrative penalty amount. The intensity of standardized discretion determines the refinement of discretion. The lower limit of the administrative penalty amount determines the minimum penalty amount. The upper limit of the administrative penalty amount determines the maximum penalty amount. Under SDEAP, violations point to different penalty ranges are refined. Misusing discretion, like in Heze City and Weihai City, will be rare. Other environmental laws like the Law of the People's Republic of China on the Prevention and Control of Water Pollution, Law of the People's Republic of China on the Prevention and Control of Soil Pollution, Law of the People's Republic of China on the Prevention and Control of Ambient Noise Pollution, and Law of the People's Republic of China on the Prevention and Control of Solid Waste Pollution are the same.

Policymakers and scholars have disagreements on the effect of SDEAP. Policymakers believe that SDEAP could balance eco-environmental protection and economic development and create a fair environment for firms[7] and provide an institutional guarantee for China's high-quality development[8]. Some scholars are skeptical about the SDEAP. They believe that administrative discretion is the space reserved for law enforcement. It allows officers to adjust penalties as new information becomes available (Habermacher and Lehmann, 2020). The control of discretion is not simply compressing the administrative discretion space as small as possible (Petersen et al., 2020). Environmental problems in China are particularly complex (Chen et al., 2019). SDEAP is a slight change in environmental policy but affects the whole situation. Government, firms, and households are all involved in it. For example, environmental penalties positively affect firms' emission reduction (He et al., 2022). Investors are sensitive to environmental penalties for firms (Wu et al., 2022). It will increase equity costs (Ding & Shahzad, 2022) and audit fees (Xin et al., 2022). That's to say, environmental penalties under SDEAP affect the firms' and households' behavior. It is a multi-agent system with a knock-on effect. It is not easy to get a conclusion consistent with reality only by discussing it from a theoretical perspective.

Given the controversy between policymakers and scholars, examining the effect of SDEAP has become a real problem for us. This study constructs a multi-agent dynamic game model, including government, firms, and households. The main contributions of this study are as follows.

1) This study solves the controversy between policymakers and scholars. There is a vague understanding of whether SDEAP helps or hinders enforcement. In this study, a multi-agent dynamic game model is constructed and simulated. The parameters in the model are estimated by the statistical data of China from 2000 to 2020. The result is persuasive for policymakers and scholars.
2) This study draws out three key elements of SDEAP. How to incorporate SDEAP into the game model is a complex problem. Few studies focus on the specific model construction of the SDEAP. This study divides SDEAP into three parts: the intensity of standardized discretion and the lower and upper limits of the administrative penalty amount. This study is an exploration from practice to the theoretical model. It is meaningful for further model construction.
3) The study conducts a multi-agent dynamic game model to assess the effect of SDEAP. Dynamic stochastic general equilibrium is applied in it. It is a methodological

5 Article 48 is shown as an example in Heze City. This article was not changed in 2015.

6 It is from the Catalogue of Administrative Penalty of Environmental Protection Administration Set by Laws.

7 30 May 2019. The Relevant Person in Charge of the Ministry of Ecological and Environment Answered the Reporter's Questions on the Guiding Opinions on Further Standardizing the Discretion of Environmental Administrative Penalty.

8 22 May 2019. The Ministry of Ecology and Environment issued One of the Bases of Guiding Opinion on Further Standardizing the Discretion of Environmental Administrative Penalty Is the Notice of the General Office of the State Council on Focusing on the Concerns of Enterprises and Further Promoting the Implementation of Policies to Optimize the Business Environment.

improvement. By solving the dynamic equilibria, we clarify the multi-agent mechanism under SDEAP. It reveals how the government, firms, and households interact. By some numerical simulations, the effects of three key elements are apparent. We put forward policy implications accordingly. It is valuable for improving environmental policy in the future.

2 Literature review

2.1 Discretion and standardized discretion of environmental administrative penalty

Since Hart proposed discretion in the mid-20th century (Hart, 1997), the debate over discretion has been protracted. The school represented by De Montesquieu (2003) advocated denying and eliminating discretion. The school represented by Frank and Bix (2017) advocated the individual initiative factor in law enforcement discretion. For all that, discretion is still applied in the legal system and evolved into two forms: judicial discretion and administrative discretion. This study reviews the literature along the research field of administrative discretion in environmental penalty.

2.1.1 Discretion of environmental administrative penalty

Discretion is unavoidable in an environmental administrative penalty (Zhang et al., 2018). Some scholars have theoretically discussed discretion. Arabadjieva (2017) believed that administrative discretion leaves space to respond to variable pollution behaviors. However, some scholars hold different views. Zhang et al.(2018) thought that discretionary power is executed differently and leads to different results, which is often controversial (Rivera & Knox, 2022). The penalty amount depends on the direction of the EPB's environmental preferences (Fang et al., 2020). The EPB pays more attention to environmental protection than economic development. The above disputes also exist in empirical studies. He et al. (2022) found an environmental deterrent effect of environmental penalties. It can encourage deterrence and improve compliance by making penalties less predictable for firms (Germani et al., 2017). There are also opposing views. Gong et al. (2019) revealed the presence of a high level of discretion and considerable inconsistency in court judgments. Kang and Silveria (2021) found heterogeneity in penalties for observably similar violations. These studies show that discretion in environmental protection may not be appropriately applied. The root of the dispute lies in the broad range of discretion.

More than that, other scholars found government firms collusion (Hu & Shi, 2021), administrative corruption (Hao et al., 2022), and other problems that lead to apparent unfairness of administrative behavior (Catalano & Pezzolla, 2017; Yamazaki & Takeda, 2017). It is inconsistent with China's high-quality development goal of both eco-environment and economic development (Jiang et al., 2022; Yuan et al., 2022).

2.1.2 Standardized discretion of environmental administrative penalty

Many scholars put forward the defect of discretion, but only a few suggested how to improve it. Duflo et al.(2018) believed regulatory discretion is extensively valued for administrative supervision. Zhu et al. (2022) thought that discretion raises concerns about weak environmental enforcement. The central government must regulate local administrative discretion. Tadaki (2020) proposed that it is necessary to reveal frontiers for formulating and engaging in discretion. This method of limiting frontiers is consistent with SDEAP. Hu and Zhu (2021) constructed an environmental penalty strategy. In this strategy, environmental protection administrative departments can use their discretion within a specific range. These studies are explorations of standardized discretion in theoretical construction.

Studies on discretion and standardized discretion are shown in Table 4. It lacks assessment for SDEAP. SDEAP has been implemented in China for several years. How effective is SDEAP? There is no conclusion so far. This study constructs a multi-agent dynamic game model to make up study gaps in the SDEAP assessment.

2.2 Multi-agent game of environmental administrative penalty

To explore the effect of environmental administrative penalties, scholars constructed game models between the government and the firm (Cai et al., 2016; Wang and Shi, 2019; He et al., 2022; Peng et al., 2022). Scholars found that the agents in the game models are multiple. Duan et al. (2016) emphasized the importance of the overall interests of society and constructed a multi-agent game model including government, firms, and social interests. Chen et al. (2019) considered consumers' supervision and analyzed the interaction among firms, governments, and the public. Jiang et al. (2019) believed that central government planners are essential. They constructed an asymmetric dynamic game model of the polluting firms, local government, and central government planners to explore the implementation process of multi-agent environmental regulation strategies. Xu et al. (2019) believed environmental services companies are essential. They built a multi-agent game model, including governments, environmental services companies, and firms. Su (2020) created a multi-agent game model among the government, waste producer, and waste recycler to study the role of government supervision. Shan et al. (2021) considered the surrounding residents' behaviors and built

TABLE 4 Studies on discretion and standardized discretion.

Perspectives	Discretion	Standardized discretion
Theoretical construction	Konstant, 2016; Arabadjieva, 2017 Zhang et al., 2018; Fang et al., 2020 Rivera & Knox, 2022	Duflo et al., 2018; Tadaki, 2020 Hu & Zhu, 2021; Zhu et al., 2022
Policy assessment	Germani et al., 2017; Yamazaki & Takeda, 2017 Gong et al., 2019; Hu & Shi, 2021 Kang & Silveira, 2021; He et al., 2022 Hao et al., 2022	This study

TABLE 5 Studies on the multi-agent game under environmental administrative penalty.

Studies	Third agent	Environmental means	Methods
Duan et al., 2016	Society	Static and dynamic punishment	Evolutionary game
Chen et al., 2019	Public	Multi-scenario punishment strategy	Evolutionary game + empirical analysis
Jiang et al., 2019	CG planners	Fiscal decentralization	Asymmetric dynamic game
Xu et al., 2019	Services companies	Third-party governance	Evolutionary game
Su, 2020	Waste recycler	Government supervision	Evolutionary game
Shan et al., 2021	Surrounding residents	Environmental NGO	Evolutionary game
Zou et al., 2022	Public	Carbon labeling system	Evolutionary game
This study	Households	SDEAP	Dynamic stochastic general equilibrium

a multi-agent game model among the government, firms, and surrounding residents. Zou et al. (2022) considered consumers' willingness to buy low-carbon products and built a 'government-firm-public' multi-agent game model. Studies are shown in Table 5.

The above studies have two weaknesses. Firstly, the environmental administrative penalty is simplified to a fixed amount. It is inconsistent with the actual situation in China. Like the example of Heze City, there are different penalties for environmental violations. In addition, households' behavior is often set as exogenous variables. However, it has been confirmed households' behavior would be affected by environmental administrative penalties (Wu et al., 2022). And it will affect firms' costs (Ding & Shahzad, 2022). To assess the SDEAP policy effectiveness, this study improves the model by dynamic stochastic general equilibrium.

2.3 Summary

As a powerful tool for environmental protection, an environmental administrative penalty has attracted extensive academic attention. The dispute has never stopped, whether it is about discretion or standardized discretion. From the perspective of study contents, variable theoretical constructions and policy assessments about the discretion of environmental administrative penalty are carried out. Scholars have been skeptical of environmental administrative discretion. It indicates that SDEAP is meaningful. However, the study on SDEAP, a new, widely practiced tool in China, is not enough. Only a few scholars studied it, and it lacks SDEAP assessment. Therefore, our study has theoretical significance. From the perspective of study methods, multi-agent game models under different environmental means were built. It provides us with a method for solving the problem. However, simplifying some variables cannot truly reflect the strength and impact of the environmental administrative penalty.

This study constructs a "government-firms-households" multi-agent game model to fill the gap. To improve the study methods, we adopt dynamic stochastic general equilibrium theory referring to Evstigneev et al. (2020). By seeking dynamic equilibrium equations and simulating the policy effect, we try to find the mechanism of SDEAP's impact on the eco-environment and economy.

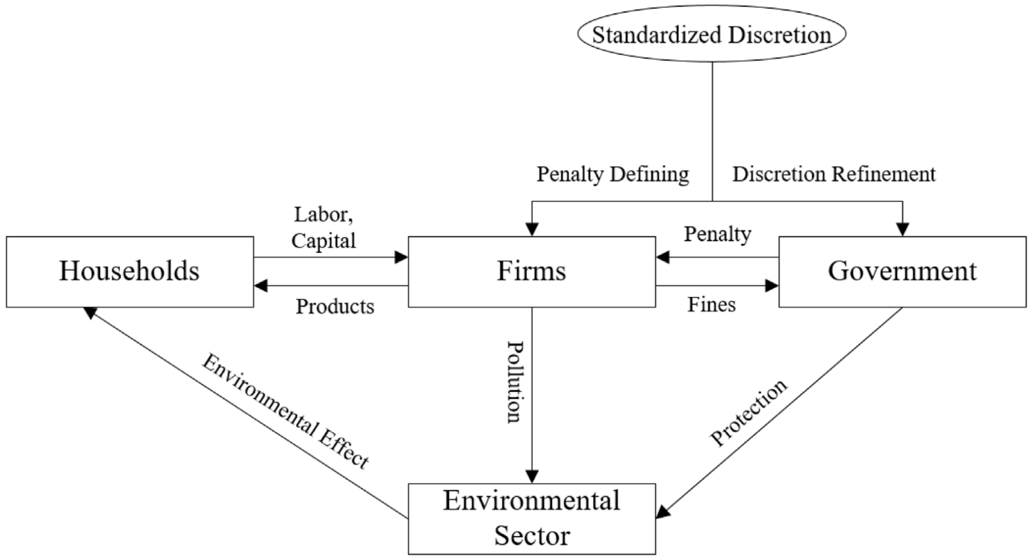

FIGURE 1
Mechanism of SDEAP.

3 The model

SDEAP has three essential elements: the intensity of standardized discretion and the lower and upper limits of the administrative penalty amount. It refines the discretion employing "Discretion Table + Formula". It can restrict the government's discretion and enable the firms to understand the consequences of pollutant emissions.

The operation mechanism is shown in Figure 1. i) For the households, they provide capital and labor for the firms. The households consume the products the firms produce and are affected by the quality of the eco-environment. ii) For the firms, they produce products by renting capital and labor. It also generates and discharges pollutants to the environmental sector, which the government penalizes. The firms will maximize their profits by coordinating output and emission reduction efforts. iii) The government puts fines according to SDEAP and enhances SDEAP construction, which can restrict firms' pollutant discharge behavior. The environmental sector is affected by the pollutants discharged. The eco-environment quality has an impact on households.

3.1 Model construction

According to Figure 1, the multi-agent model is constructed as follows.

3.1.1 Households

In the model, the households are homogeneous. Each has the same preference and can survive indefinitely. The households' utility is affected by consumption, labor, and eco-environment quality (Gao & Xin, 2022). The utility function is the Coefficient of Relative Risk Aversion (CRRA). It is given by

$$U(C_t, N_t, Q_t) = \frac{C_t^{1-\theta_1}}{1-\theta_1} - \frac{N_{f,t}^{1+\theta_2}}{1+\theta_2} + \eta \ln Q_t \tag{1}$$

where C_t and $N_{f,t}$ are the consumption and labor supply, $\theta_1 > 0$ and $\theta_2 > 0$ are the inverse of consumption elasticity and inverse of labor supply elasticity, η is the utility coefficient of eco-environment quality, Q_t represents the eco-environmental quality. We assume the relative risk aversion elasticity to the eco-environmental quality is 1. Therefore, the CRRA utility function is logarithmic. For households, expenditure includes consumption and investment. Income has capital interests and labor earnings. The households maximize lifetime utility under the constraint. It is given by

$$\max E_0 \sum_{t=0}^{\infty} \beta^t \left(\frac{C_t^{1-\theta_1}}{1-\theta_1} - \frac{N_{f,t}^{1+\theta_2}}{1+\theta_2} + \eta \ln Q_t \right) \tag{2}$$

$$\text{s.t. } C_t + I_t = R_t K_{f,t} + W_t N_{f,t} \tag{3}$$

where E_0 is the conditional expectation operator, $\beta (0 < \beta < 1)$ is the discount factor, $K_{f,t}$ is the capital investment of households, R_t and W_t are the return on capital, and the wage rate, I_t is the investment. The capital stock evolves as

$$I_t = K_{f,t+1} - (1-\delta) K_{f,t} \tag{4}$$

where $0 < \delta < 1$ is the depreciation rate of capital.

3.1.2 Firms

We use the Cobb-Douglas function for the firm's production function as follows:

$$Y_t = A_t K_{m,t}^{\alpha} N_{m,t}^{1-\alpha} \tag{5}$$

where Y_t is the output, $\alpha (0 < \alpha < 1)$ is the capital elasticity, $K_{m,t}, N_{m,t}$ are the capital and labor invested by firms, A_t denotes an aggregate technical shock, which follows the stationary stochastic process:

$$\ln A_t = (1 - \rho_A) \ln A^* + \rho_A \ln A_{t-1} + \varepsilon_{A,t} \tag{6}$$

where ρ_A is the coefficient of the technology shock, A^* is the steady-state value of technology, $\varepsilon_{A,t} \sim N(0, \sigma_A^2)$ denotes the technical shock.

The pollutant emission X_t of the firms is given by

$$X_t = \frac{\kappa Y_t}{PR_t} \tag{7}$$

where PR_t is the emission reduction efforts, κ is the pollutant emission coefficient, which measures pollutant emission per unit of output.

$f(X_t)$ is the fines of environmental administrative penalty. The government makes it based on SDEAP. We learned from the Shandong Province Standardized Discretion of Environmental Administrative Penalty to construct the equation. It is given by

$$f(X_t) = L_t + \frac{1}{2}(H_t - L_t)\frac{O_t - 1}{B_t - 1} \tag{8}$$

where L_t and H_t are the lower limit and upper limit of the penalty amount, B_t is the refinement level of SDEAP, and O_t is the level of pollutant emissions in the *Discretion Table*. Since the upper and lower limits of the penalty amount are parts of SDEAP. We suppose it follows the stationary stochastic process:

$$\ln L_t = (1 - \rho_L) \ln L^* + \rho_L \ln L_{t-1} + \varepsilon_{L,t} \tag{9}$$

$$\ln H_t = (1 - \rho_H) \ln H^* + \rho_H \ln H_{t-1} + \varepsilon_{H,t} \tag{10}$$

where ρ_L and ρ_H are the coefficients of the lower and upper limits shocks, L^* and H^* are the steady-state values of the lower and upper limits, $\varepsilon_{L,t} \sim N(0, \sigma_L^2)$ and $\varepsilon_{H,t} \sim N(0, \sigma_H^2)$ are the shocks of the lower and upper limits.

The refinement level B_t depends on the intensity of standardized discretion DS_t. It is given by

$$B_t = \lambda \ln DS_t \tag{11}$$

where λ is a coefficient of refinement level. We assume that it follows the stationary stochastic process

$$\ln DS_t = (1 - \rho_{DS}) \ln DS^* + \rho_{DS} \ln DS_{t-1} + \varepsilon_{DS,t} \tag{12}$$

where ρ_{DS} is a coefficient of standardized discretion, DS^* is the steady-state value of the intensity of standardized discretion, $\varepsilon_{DS,t} \sim N(0, \sigma_{DS}^2)$ is the shock of the intensity of standardized discretion.

The level of pollutant emissions O_t follows the principle of administrative discretion standards. The relationship between administrative penalties and pollutant emissions exceeding the regulations is approximately linear within a specific range. It is given by

$$O_t = \psi \frac{X_t}{X_l} \tag{13}$$

where X_l is the length of the standardized penalty range, ψ represents the adjustment coefficient.

The firms maximize their profits by adjusting production and emission reduction. The firm's profit is given by

$$\pi_t = Y_t - K_{m,t}R_t - N_{m,t}W_t - \chi PR_t - f(X_t) \tag{14}$$

where χ is the unit cost of emission reduction efforts.

3.1.3 Government

The government gets revenue by collecting environmental penalties and then puts it under standardized discretion. The constraint function is given by

$$f(X_t) = DS_t \tag{15}$$

3.2 Model solution

To fully consider the impact of eco-environment quality on households, firms, and government, we assume that.

1) The eco-environment quality is a dynamic evolution process with self-purification ability.

$$Q_t = h\bar{Q} + (1 - h)Q_{t-1} - X_t \tag{16}$$

where $\bar{Q}$ is the initial eco-environmental quality with no pollutant emission, $h(0 < h < 1)$ is the self-purification ability, Q_{t-1} is the eco-environmental quality at the last period.

2) The market-clearing state of production is given by

$$Y_t = C_t + I_t + DS_t \tag{17}$$

3) The market-clearing state of labor is given by

$$N_t = N_{f,t} = N_{m,t} \tag{18}$$

4) The market-clearing state of capital is given by

$$K_t = K_{f,t} = K_{m,t} \tag{19}$$

The model is solved by the Lagrange multiplier method. The evolutionary equilibrium solution of this multi-agent dynamic game model meets the following equations.

TABLE 6 Values of equilibrium solution parameters.

Parameter	Definition	Value	References
β	Discount factor	0.98	Zhang, 2009
δ	The depreciation rate of capital	0.035	Li and Liu, 2017
θ_1	The inverse of consumption elasticity	0.8	Zhao et al., 2020
θ_2	The inverse of labor supply elasticity	2	Tu & Wang, 2022
α	Capital elasticity	0.5	Liu and He, 2021
κ	Pollutant emission coefficient	0.5	Liu and He, 2021
X_l	Standardized penalty range	3	SDEAP of Shandong Province in China
h	Self-purification ability	0.1	Angelopoulos et al., 2010

TABLE 7 The prior distribution of parameters and Bayesian estimation results.

Parameter	Definition	Prior mean	Prior distribution	Post mean	90% CI
η	Coefficient of eco-environment quality	2	Normal	2.0000	[1.9988 2.0013]
λ	Coefficient of refinement level	0.5	Normal	0.4999	[0.4983 0.5018]
ψ	Adjustment coefficient	1.1	Normal	1.1001	[1.0991 1.1013]
χ	The unit cost of emission reduction efforts	0.045	Normal	0.0451	[0.0437 0.0466]
$\bar{Q}$	Initial eco-environmental quality	1	Normal	1.0003	[0.9985 1.0016]
ρ_A	Coefficient of the technology shock	0.7	Beta	0.6997	[0.6979 0.7015]
ρ_{DS}	Coefficient of the intensity of standardized discretion shock	0.7	Beta	0.7001	[0.6985 0.7022]
ρ_L	Coefficient of the lower limits shock	0.7	Beta	0.7000	[0.6984 0.7015]
ρ_H	Coefficient of the upper limits shock	0.7	Beta	0.7000	[0.6979 0.7016]
$e_{A,t}$	Technical shock	0.5	Inv. Gamma	0.5001	[0.4986 0.5020]
$e_{DS,t}$	The intensity of standardized discretion shock	0.5	Inv. Gamma	0.5002	[0.4983 0.5018]
$e_{L,t}$	Lower limit shock	0.5	Inv. Gamma	0.4998	[0.4981 0.5015]
$e_{H,t}$	Upper limit shock	0.5	Inv. Gamma	0.5002	[0.4987 0.5019]

1) The relationship between wage rate, consumption, and labor supply is expressed as

$$W_t = N_t^{\theta_2} C_t^{\theta_1} \tag{20}$$

2) The relationship between consumption change rate and return on capital is expressed as

$$\frac{C_{t-1}^{-\theta_1}}{C_t^{-\theta_1}} = \beta(R_t + 1 - \delta) \tag{21}$$

3) The relationship between capital, return on capital, output, lower limit, upper limit, refinement level of SDEAP, and emission reduction efforts are expressed as

$$K_t = \frac{1}{R_t}\alpha Y_t\left(1 - \frac{\psi\kappa(H_t - L_t)}{2(B_t - 1)X_l PR_t}\right) \tag{22}$$

4) The relationship between labor supply, wage rate, output, lower limit, upper limit, refinement level of SDEAP, and emission reduction efforts is expressed as

$$N_t = \frac{1}{W_t}(1-\alpha)Y_t\left(1 - \frac{\psi\kappa(H_t - L_t)}{2(B_t - 1)X_l PR_t}\right) \tag{23}$$

5) The relationship between emission reduction efforts, output, lower limit, upper limit, and refinement level of SDEAP is expressed as

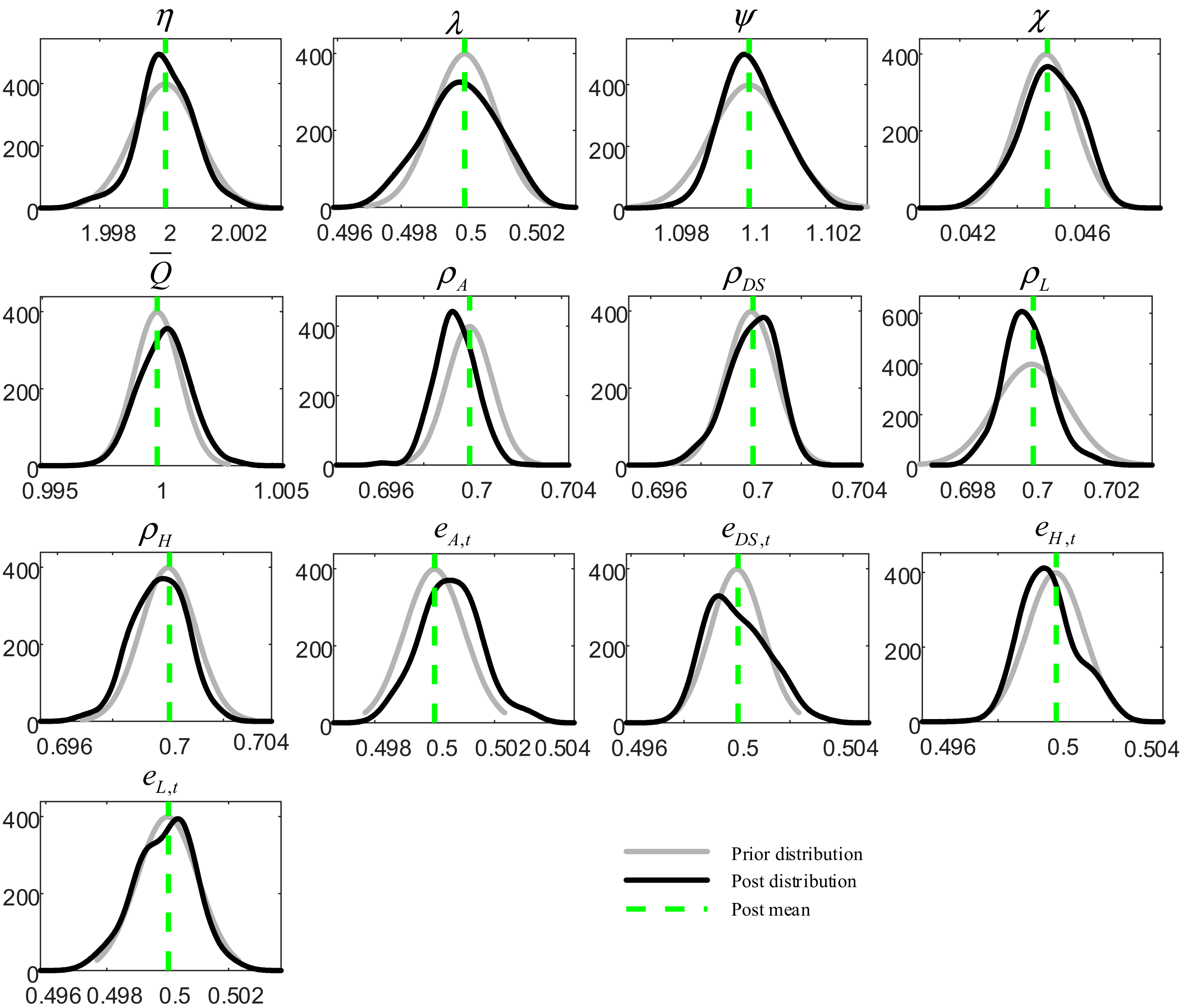

FIGURE 2
Results of bayesian estimation.

$$PR_t = \sqrt{\frac{\psi\kappa Y_t (H_t - L_t)}{2X_l\chi(B_t - 1)}} \tag{24}$$

4 Parameters calibration and estimation

The above solutions are implicit. Therefore, we need to calibrate and estimate the parameters. The parameter values such as $\beta, \delta, \theta_1, \theta_2, \alpha, \kappa, X_l, h$ are available in previous studies. We calibrate these parameters based on existing studies. Other parameter values are unavailable. We use the Bayesian method to estimate the rest parameters by the statistical data of China from 2000 to 2020.

4.1 Parameters calibration

Regarding the existing studies, we calibrate the parameters. The results are shown in Table 6.

4.2 Parameters estimation

We set $\eta = 2$, $\lambda = 0.5$, $\psi = 1.1$, $\chi = 0.045$. It is assumed that these parameters obey Normal Distribution. We set $\rho_A, \rho_{DS}, \rho_L, \rho_H$ at 0.7 and set $e_{A,t}, e_{DS,t}, e_{L,t}, e_{H,t}$ at 0.5. Referring to Smets & Wouters (2004), it is assumed that the prior means of coefficients obey Beta Distribution and the prior means of shocks follow Inv. Gamma Distribution. The results are shown in Table 7; Figure 2.

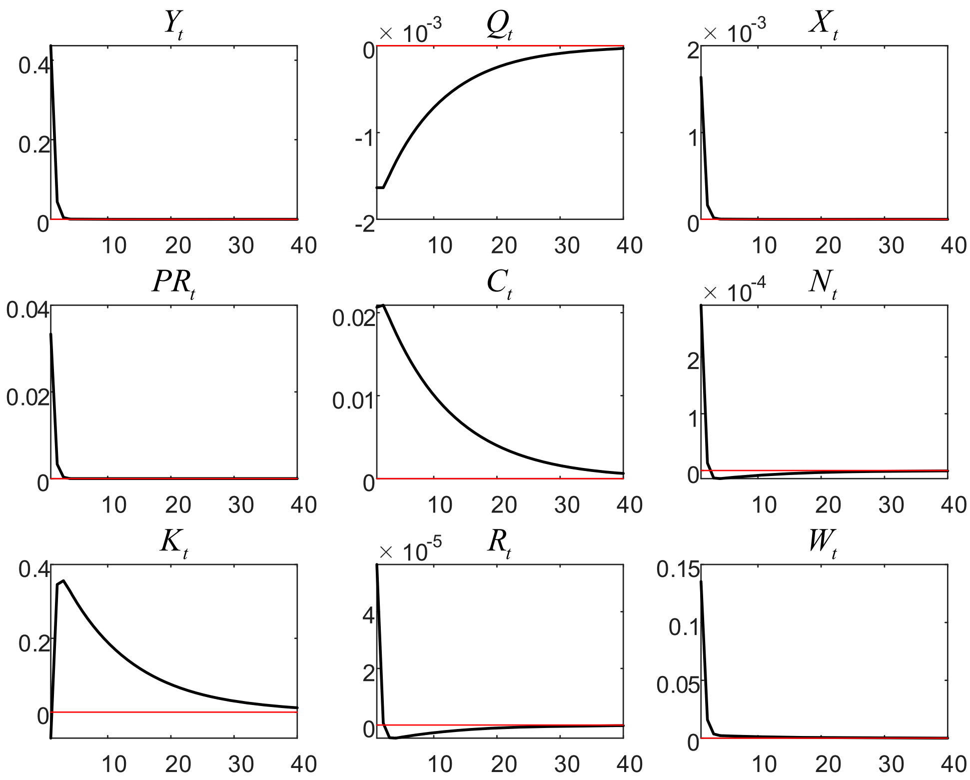

FIGURE 3
The impulse response of intensity of standardized discretion.

5 Dynamic effect and conduction mechanism

After estimating parameters, the dynamic numerical simulations of SDEAP are carried out. We analyze the impulse responses of the intensity of standardized discretion and the lower and upper limits of the administrative penalty amount.

5.1 Dynamic effect analysis of intensity of standardized discretion

The dynamic effect of the intensity of standardized discretion is shown in Figure 3. i) For the government, the balance between eco-environment protection and economic development matters. The intensity of standardized discretion shock has a positive effect on output but a negative effect on eco-environment quality in the short term. In the long term, the negative effect on the eco-environment quality will gradually decrease and close to zero. ii) For the firms, a fair business environment under standardized discretion promotes firms to increase output. So, the capital increases, and labor demand increases first and then decreases. At the same time, the wage increases, and the return on capital increases first and then decreases. Firms will improve their emission reduction efforts. However, the pollution reduction due to emission reduction efforts is less than the pollution generated by output. Therefore, pollutant emissions will still increase in the first three periods. iii) For the households, total incomes increase with labor supply and capital investment. The increased income is partly used for capital investment and partly for consumption.

In the short term, standardized discretion increases output but decreases eco-environment quality. It is explained as follows. A fair business environment is created for firms under standardized discretion. A suitable business environment helps promote the output of firms (Qi et al., 2022). Pollutants will inevitably be generated in the production process (Grossman and Krueger, 1992). As Germani et al. (2017) proposed, standardized discretion reduces the unpredictability of the penalty amount. The deterrent effect is weakened (He et al., 2022), causing firms may not to make efforts to reduce emissions. Due to insufficient emission reduction efforts, production will inevitably lead to pollutant emissions. Under this condition, the pollutant emissions exceed the self-purification ability of the eco-environment. Therefore, the increase in output in the short term leads to the rise of pollutant emissions. The negative

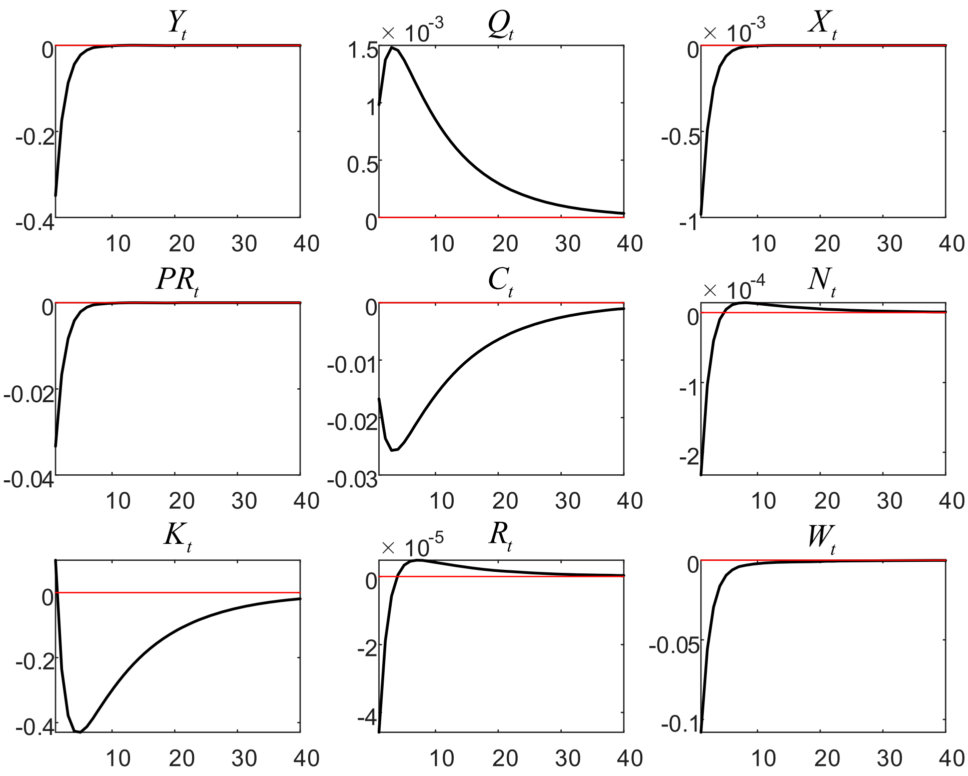

FIGURE 4
The impulse response of lower limit.

effect on the eco-environment quality is evident at the beginning. In a short period, The effect is not very ideal. The result is different from that of Duflo et al.(2018), Tadaki (2020), Kang and Silveria (2021), etc.

In the long term, it is consistent with the Environmental Kuznets Curve (EKC). As the effect on output gradually weakens, pollutant emissions will no longer increase. In addition, the eco-environment has a self-purification ability. The negative impact on the eco-environment will eventually be eliminated. Since China's development stage is still on the left side of EKC, the eco-environment has slightly deteriorated with the economic growth. After reaching the 'inflection point', the eco-environment will be significantly improved.

5.2 Dynamic effect analysis of lower limit of administrative penalty amount

The dynamic effect of the lower limit is shown in Figure 4. i) For the government, the lower limit has a positive impact on eco-environment quality but a negative effect on the output. This negative effect gradually disappears in the third period. ii) For the firms, the output will be reduced so as not to touch the lower limit of punishment. So, the capital decreases, and labor demand decreases first and then increases. At the same time, the wage decreases, and the return on capital decreases first and then increases. Although firms reduce their emission reduction efforts, pollutant emissions still decrease due to the reduction of output. iii) For the households, total incomes decrease with the decreases in labor supply and capital investment. The consumption also decreases.

In the short term, setting the lower limit increases eco-environment quality but decreases output. It is explained as follows. The lower limit sets the minimum violation cost. The penalty amount is lower than the cost of clean technology innovation. Firms have no motivation to carry out cleaner production. However, pollution emissions without cleaner production will exceed the standard and result in penalties. Firms would reduce output to reduce pollutant emissions to avoid the lower limit. Furtherly, emission reduction efforts are meaningless when the emissions are below the lower limit. Firms want to minimize emission reduction efforts and decrease costs to maximize profits.

In the long term, the output reduction will gradually disappear because the firms will find the most considerable output under the constraint of the lower limit. A balance will be formed in the long term.

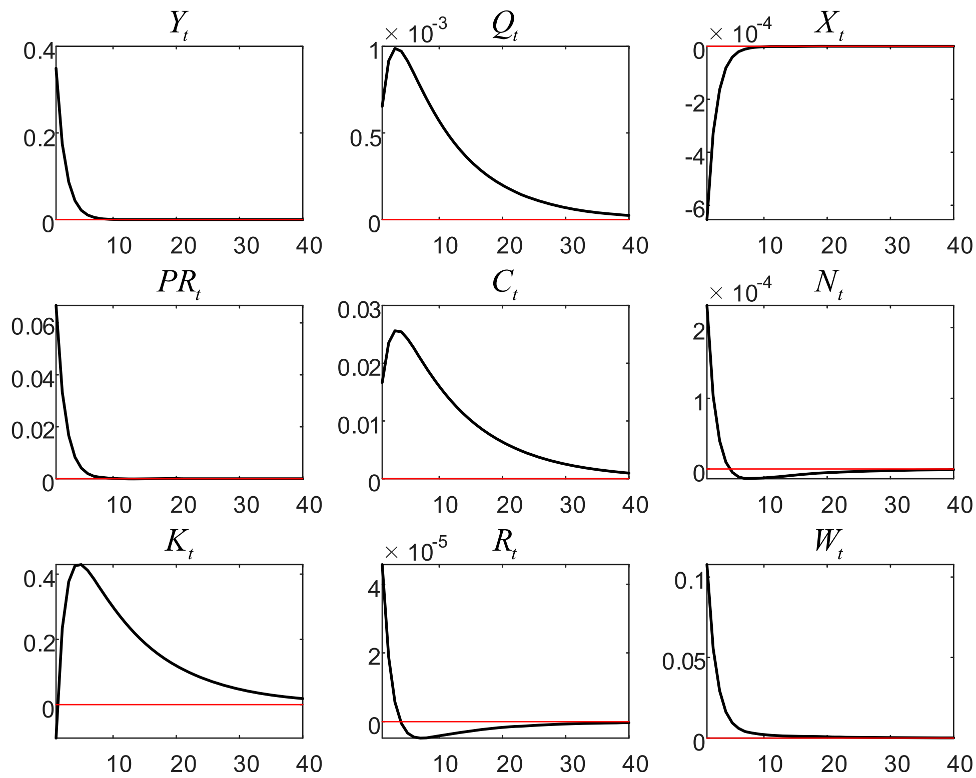

FIGURE 5
The impulse response of the upper limit.

5.3 Dynamic effect analysis of upper limit of administrative penalty amount

The dynamic effect of the upper limit is shown in Figure 5. i) The upper limit positively affects eco-environment quality and output for the government. It balances eco-environment protection and economic development. ii) For the firms, they increase output and emission reduction efforts. So, the capital increases, and labor demand increases first and then decreases. At the same time, the wage increases, and the return on capital increases first and then falls. Under the upper limit, the pollutant reduction due to emission reduction efforts is more than the pollutant generated by output. Therefore, the pollutant emission is reduced. iii) For the households, total incomes increase with labor supply and capital investment. The increased income is partly used for capital investment and partly for consumption.

In the short term, the upper limit will promote output and emission reduction efforts at the same time. The result coincides with Cai et al. (2016). A high penalty amount has a deterrent effect. It is unrealistic to reduce pollution emissions simply by reducing output. High penalty amounts can force firms to reduce emissions by promoting clean energy and increasing pollution control equipment and product process innovation (Bu & Shi, 2021). These are firms' emission reduction efforts. Then the pollutant emission will be greatly reduced. Under the eco-environmental self-purification ability, eco-environmental quality is improved significantly in the short term. Therefore, it can reduce pollutant emissions, improve the eco-environment quality, and achieve dual benefits for the eco-environment and economy.

In the long term, the positive effect on output gradually decreases, while the positive impact on the eco-environment lasts. It is because the use of clean energy, pollution control equipment, and product process innovation could reduce pollutant emissions for a long time.

5.4 Sensitivity analysis

This chapter examines the robustness of the model. We selected three key variables: output, eco-environment quality, and pollutant emissions. The dynamic effects are shown in Figure 6 when the shocks fluctuate up and down by 15%. In Figure 6, lines 1–3 respectively correspond to the

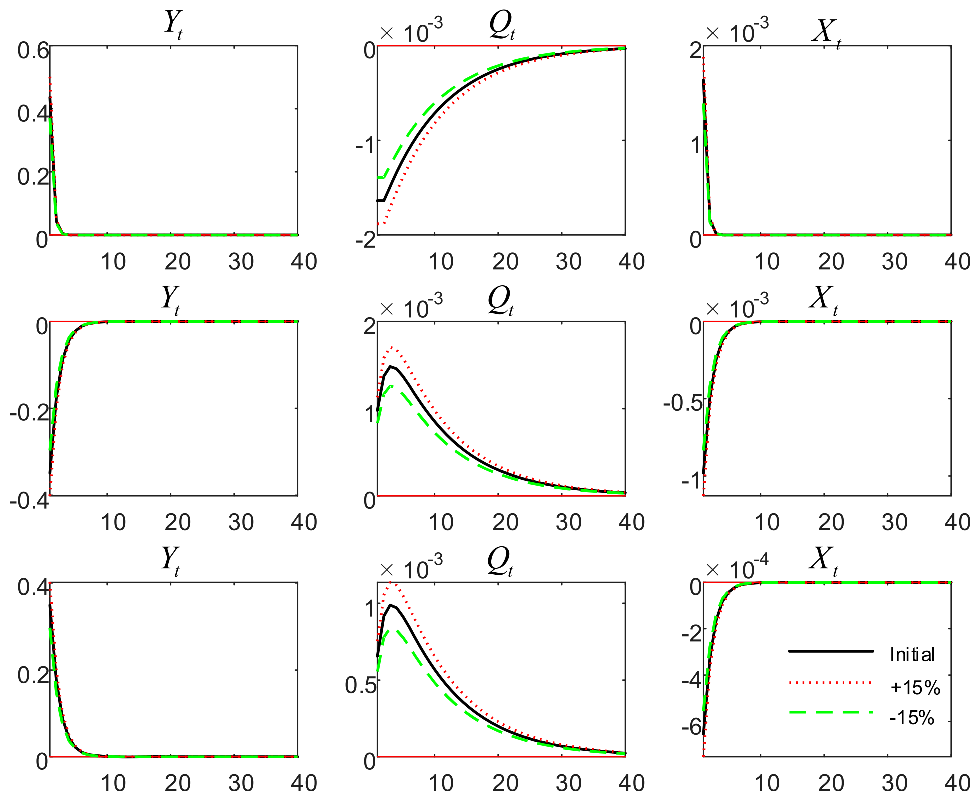

FIGURE 6
Sensitivity analysis.

impact of a 15% fluctuation in the intensity of standardized discretion, the lower limit, and the upper limit. We find that when each shock fluctuates up and down by 15%, the effect directions do not change. The selection of the initial value of external impact does not vary the overall change trend of variables. The research conclusion has high reliability.

6 Conclusion and implications

6.1 Conclusion

From the legal rules and enforcement process, we draw out three key elements of SDEAP: the intensity of standardized discretion and the lower and upper limits of the administrative penalty amount. By constructing a multi-agent dynamic game model, we studied the dynamic effect of SDEAP on the economy and eco-environment. The results show that i) The intensity of standardized discretion will promote output growth and improve emission reduction efforts. But it has a specific adverse effect on eco-environmental quality. This negative effect is mainly because the emission reduction efforts of firms are lower than the output increase. The negative effect on eco-environmental quality will gradually disappear in the long run. ii) The lower limit will simultaneously reduce output and emission reduction efforts. The output decline will reduce pollutant emissions and positively affect the eco-environment. It is not conducive to economic development in the short term. The negative effect on economic development will gradually disappear in the long run. iii) The upper limit has a positive effect on the eco-environment and output simultaneously. It is conducive to the joint development of the economy and eco-environment.

6.2 Policy implications

Overall, SDEAP restricts the broad range of discretion. It can promote economic growth, but discretion should not be excessively squeezed. In the short term, SDEAP cannot achieve the high-quality development goal of the joint development of the economy and eco-environment. In a long time, it can balance eco-environment quality and economic development. The following policy implications are put forward.

1) As a new constraint method, there are still many problems in SDEAP. In the current SDEAP construction, more attention is paid to standardized discretion. The other two key elements (lower and upper limits) are not concerned they deserved. The lower and upper limits of the administrative penalty amount need to be adjusted in time with the economic development. Especially the upper limit, it can achieve the dual goals of eco-environment protection and economic development. It plays an essential role in harmonizing eco-environment protection and economic development.
2) It is a long way to achieve the high-quality development goal of the joint development of the economy and eco-environment. At the initial stage of policy adjustment, it may be impossible to consider eco-environment protection and economic development. In an extended period, the high-quality development goal can be achieved. Therefore, we should look at short-term and long-term effects.

6.3 Limitations and further researches

This study contends with several limitations. To highlight the effect of SDEAP, we simplified governments into one department. In reality, governments in China are divided into central and local governments. They have different government powers. For example, the Central Regulations on Supervision of Ecological Environment Protection was issued in 2019. The central government supervises local governments. Future works could study the role of central government supervision in SDEAP. Besides, environmental non-governmental organizations (ENGOs) are critical social forces. ENGOs are effective bridges connecting the government, firms, and households. Future work could take ENGO as a player in the multi-agent game model.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

XM: Methodology, Formal analysis, Software, Data processing, Writing-original draft, Investigation. BX: Conceptualisation, Methodology, Investigation, Writing-review and editing, Supervision, Validation, Resources. GW: Conceptualisation, Investigation, Validation.

Funding

This work was supported by the National Planning Office of Philosophy and Social Science of China (Grant No. 21BJY206), and Social Science Planning Project of Shandong Province (Grant No. 19BJCJ67).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 06 January 2023
DOI 10.3389/fenvs.2022.1096087

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OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Environmental Economics and Management, a section of the journal Frontiers in Environmental Science

RECEIVED 11 November 2022
ACCEPTED 21 December 2022
PUBLISHED 06 January 2023

CITATION
Yang Q, Pu L, Jiang C, Gong G, Tan H, Wang X and He G (2023), Unveiling the spatial-temporal variation of urban land use efficiency of Yangtze River Economic Belt in China under carbon emission constraints.
Front. Environ. Sci. 10:1096087.
doi: 10.3389/fenvs.2022.1096087

Unveiling the spatial-temporal variation of urban land use efficiency of Yangtze River Economic Belt in China under carbon emission constraints

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Under the constraint of carbon emission, measuring and analyzing the spatial-temporal evolution characteristics of urban land use efficiency in the Yangtze River Economic Belt is the inherent requirement of its ecological protection and sustainable development. In this paper, we calculated the urban land use efficiency of 107 cities in the Yangtze River Economic Belt from 2006 to 2020 by using the SBM-Undesirable model with unexpected output, and analyzed its temporal evolution trend and spatial correlation relationship by using kernel density and spatial autocorrelation method. The results showed that: except in 2020, the urban land use efficiency was generally low due to the COVID-19 epidemic, and the urban land use efficiency in other years was mostly concentrated in the middle levels, and showed a trend of slow fluctuation and rise year by year. The difference of urban land use efficiency level between regions increased, and the dispersion degree in upstream, midstream and downstream increased with each passing year. Urban land use efficiency spatial imbalance was significant, and the urban land use efficiency level of large and medium-sized cities was generally lower than that of cities with low economic development level. The spatial correlation was weak, and the global spatial autocorrelation was basically insignificant, while the local spatial agglomeration areas were mainly distributed in the upstream and downstream regions, with a small distribution range and weak spatial interaction. The distribution areas of the standard deviation ellipse were gradually flattened, and the center of gravity as a whole shift significantly to the southwest. The research results are helpful to understand the development history and future trend of urban land use efficiency in various regions, and propose that cities should consider the impact of public crisis events in advance, reasonably control the scale of land expansion, and lead coordinated development and other reasonable suggestions when formulating land use policies.

KEYWORDS

urban land use efficiency, carbon emissions, Yangtze River Economic Belt, sustainable development, SBM-undesirable model

1 Introduction

Land is the material carrier of economic, social and ecological systems, the foundation of human survival and development, and occupies an extremely important position in human society (Sun et al., 2020). As an important part of land resources, land is the basic condition of a city's existence and development, and its utilization efficiency is closely related to the social and economic development of the city and the construction of human settlements (Wei et al., 2020). Globally, the urbanization process is accelerating, with urbanization rates exceeding 50%, resulting in great changes in urban land use, resource demands and ecological and environmental pressure, which is a common challenge faced by all countries. In addition, previous studies have demonstrated that the increase in urban land use has a significant impact on carbon emissions, which in turn will affect the global ecosystem (Carpio et al., 2021; Wang et al., 2021). In this context, improving urban land use efficiency (ULUE) has been considered as a better way to promote the long-term sustainable development of cities in the future (Bobylev, 2009). Therefore, it is of great significance to scientifically evaluate the ULUE considering carbon emissions to promote the low-carbon utilization of urban land and optimize the allocation of land resource.

Since the reform and opening up, China's economy has entered a high-speed development stage, and the urbanization process is accelerating. The Statistical Yearbook of Urban Construction in China shows that from 1978 to 2020, the urbanization rate increased from 17.92% to 63.89% (Zhang et al., 2022). In order to meet the needs of urbanization, the urban land area is also expanding. However, while the expansion of urban space brings economic benefits, it also creates numerous problems. On the one hand, unreasonable urban planning and uncontrolled expansion of urban space cause serious resource idleness, resulting in inefficient urban land use (Long and Qu, 2018). On the other hand, in the process of urbanization, carbon emissions from industries, infrastructure construction and transportation will exert great pressure on the sustainable development of China (Lu et al., 2022). Therefore, the Chinese government has proposed land use policies such as strictly controlling the scale of construction land and vigorously promoting the construction of a land-saving and intensive land use system in order to solve problems such as rough land use and environmental pollution and promote the construction of a new type of urbanization (Deng, 2021).

As an important development axis in the "T" spatial strategic pattern of China's territorial development and economic layout (Bian et al., 2021), the Yangtze River Economic Belt (YREB) accounts for more than 40% of the country's population and gross domestic product (GDP), and has become one of the strongest regions in China in terms of comprehensive strength. High-intensity industrial activities and energy consumption, carbon emissions and the pressure of urban land resources in this area have restricted the sustainable development of this area (Wang et al., 2022). The development space and regional hinterland of the YREB are extremely vast, accounting for about 21.35% of the total land area of China. It spans the east, middle and west of China, with significant regional differences, and the contradictions of unbalanced and uncoordinated economic development of cities in the region are more prominent. Land use will not only bring social and economic benefits, but also have certain negative effects on ecology. High land use efficiency is to pursue the high output of economic and social benefits under reasonable input and the lowest possible ecological destructive output. Under the constraint of carbon emission, carbon emissions are taken as the measurement standard of ecological damage, and the value directly affects the level of land use efficiency. At the same time, the addition of unexpected outputs makes the measurement results more reasonable and reliable. In conclusion, based on the important strategic position and significant regional differences of the YREB, it is of great significance to discuss the regional ULUE and its spatial differences considering carbon emissions, so as to improve ULUE, promote sustainable land use and narrow the regional differences.

In view of this, based on panel data of 107 prefecture-level and above cities in the YREB, this paper uses SBM-Undesirable (SBM-UN) model to calculate the land use efficiency of cities in the YREB from 2006 to 2020. Moreover, with the help of ArcGIS software, kernel density estimation model, exploratory spatial data analysis (ESDA) method and standard deviational ellipse, the spatial and temporal evolution characteristics and regional differences of ULUE in the YREB are dissected in order to provide targeted theoretical support and decision-making reference for improving ULUE and promoting sustainable and coordinated regional development.

The structure of this article is as follows. Section 2 reviews the existing studies on ULUE. Section 3 presents the case study area, data, and methodology. Section 4 shows the results of the analysis. Section 5 discusses the findings and presents our recommendations. The last section concludes the study.

2 Literature review

Urban land use efficiency describes the benefits of unit urban land, and is an important index to measure the rationality of land resource development and utilization. With the rapid development of social economy, people gradually realize that improving the efficiency of urban land use is the key to fundamentally solving the contradiction between land supply and demand. Therefore, in recent years, scholars have conducted extensive discussions on this issue. Scientific evaluation of ULUE is the starting point to explore how to realize rational development and utilization of urban land, and it is also the focus of current research.

The evaluation methods of ULUE mainly include comprehensive evaluation method, parametric analysis method represented by stochastic frontier method (SFA) and non-parametric analysis method marked by data envelopment analysis method (DEA). For example, Chen et al. (2007) used hierarchical analysis (AHP) and entropy method (EM) to define the weights of regional land use efficiency evaluation indicators. Then, the multi-factor comprehensive evaluation method was used to analyze the land use efficiency and its development in Zhanjiang City. In evaluating the land use efficiency of 36 mining cities in western China, Yuan et al. (2019) adopted the improved entropy weight method to select indicators and calculate the efficiency value. However, the comprehensive evaluation method is subjective in determining the weights of measurement indicators, which can lead to the deviation of the efficiency measurement results. Therefore, more and more scholars choose parametric and non-parametric methods to analyze ULUE. Liu et al. (2020) evaluated ULUE in China by using a single-stage SFA model and analyzed the potential for ULUE improvement. Dong et al. (2020) used SFA to calculate the ULUE of 108 cities in the YREB and analyzed the interaction between ULUE, industrial transformation, and carbon emissions. Zhu et al. (2019) used the SBM model to measure the ULUE of 35 megacities in China and found that the level was low and showed a slow growth trend.

As far as the research objects of ULUE is concerned, it mainly focuses on industry and efficiency evaluation. With the attention of many scholars on ULUE, the research on the driving factors and influence mechanism of ULUE has become a research hotspot. For example, in terms of industry, Xie and Wang (2015) analyzed the spatial differences in urban industrial land use efficiency and the dynamic changes in urban industrial land total factor productivity in six major economic regions in China. On the evaluation of ULUE and its influencing factors, Xue et al. (2022) evaluated the land use efficiency of 57 cities in the Yellow River Basin, and discussed its influencing factors. It was found that the proportion of secondary industries, population density, and introduction of foreign capital contributed significantly to land use efficiency in the basin, while the urbanization of land and environmental regulations had negative effects on the land use efficiency. Gao et al. (2020) took the Wuhan metropolitan area in China as an example and found that the regional economic integration can promote the optimal allocation of resources and thus improve ULUE.

Regarding the selection of ULUE indicators, first of all, in terms of the selection of input variables, most researchers agreed that land, capital and labor could be used (Gao et al., 2022). In contrast, the selection of output variables is not quite the same. Previously, some scholars only selected economic indicators as a single output variables (Huang et al., 2016). However, with the deepening of the research on ULUE, researchers began to select output variables from economic, social and environmental aspects (Yang et al., 2022). In the process of urban land use, undesired outputs such as sewage and exhaust gases were also generated. Therefore, some scholars have included pollutants as undesired outputs in the ULUE evaluation system (Pan et al., 2022; Zhang et al., 2022). For example, Wang et al. (2022) included carbon emissions as an undesired output in their comparative study of construction land use efficiency in China and United States; Lu et al. (2022) similarly measured ULUE in three major urban agglomerations in China using carbon emissions as an undesired output and found that technological progress was the main driver of land use efficiency improvement in each urban agglomeration. However, up to now, the research on ULUE under the constraint of carbon emission is still relatively few.

Through sorting out the relevant research progress, we can find that the existing research results are quite rich, but the complete theoretical system has not been fully formed, and there are still some deficiencies: first, the definition of the concept is not clear enough. Researchers have not yet reached a consensus on the connotation of urban land use efficiency, and their definitions are usually different based on different research perspectives; Secondly, in terms of the selection of evaluation methods, the traditional DEA model is often used at present, which not only ignores the relaxation of input and output, but also fails to bring the unexpected output into the study; Third, the efficiency measurement is not comprehensive enough. When measuring the land use efficiency, existing studies usually only consider the economic and social benefits brought by land use, but less consider its negative impact on the environment. Especially in the context of carbon emission reduction, the measurement of land use efficiency has not been paid enough attention to, which makes the measurement of urban land use efficiency inaccurate.

Based on the previous research progress and deficiencies, this paper takes 107 cities in the YREB as research objects, incorporates carbon emissions into the measurement framework as unexpected output, and uses the relaxation based unexpected output measurement model (SBM-UN) to reasonably measure the unexpected output, and reveals the temporal and spatial evolution characteristics of ULUE. It provides scientific reference for low carbon efficient utilization of cities in the YREB.

3 Materials and methods

3.1 Study area

The research area of this paper is cities above the prefecture level in the YREB. Due to the change of administrative system, Chaohu, Bijie, Tongren, and Pu'er, which were eliminated or added during the period of 2006–2020, were excluded, and the data caliber was processed consistently, finally 107 cities in the YREB were obtained. The YREB covers 11 provinces and municipalities, including Shanghai, Jiangsu, Zhejiang, Anhui, Jiangxi, Hubei, Hunan, Chongqing, Sichuan, Yunnan, and Guizhou. It is divided into the upstream, midstream and downstream. The downstream area includes three provinces and one municipality, including Shanghai, Jiangsu, Zhejiang, and Anhui, covering an area of about 3,50,300 square kilometers, accounting for 17.1% of the YREB. The midstream area includes Jiangxi, Hubei and Hunan provinces, covering an area of 564,600 square kilometers, accounting for 27.5% of the YREB. The upstream area includes Chongqing, Sichuan, Guizhou and Yunnan, covering an area of 1,137,400 square kilometers, accounting for 55.4% of the YREB. See Figure 1 for details.

3.2 The index system

3.2.1 Indicator selection

When constructing the systematic evaluation index system of ULUE, the study not only considered the benefits of comprehensive land use on economic, social and environmental development, but also considered the adverse effects of land use on the environment. Referring to the existing research results, the study followed the scientific, comparable and representative principles of indicator selection, selected indicators that can reflect ULUE to a great extent, and built a comprehensive evaluation indicator system for ULUE (Table 1), as shown below.

(1) Input indicators: ①Land input. Urban land is the basic input element and spatial carrier of urban activities (Chen et al., 2022), and the area of urban built-up area shows the extent of urban space (Kityuttachai et al., 2013), which can reflect the status of urban land use. Therefore, the urban construction land area is chosen to represent land input in this paper. ②Capital input. The amount of investment in fixed assets is an important basis for the national investment plan and control of investment scale (Meng et al., 2021), so the

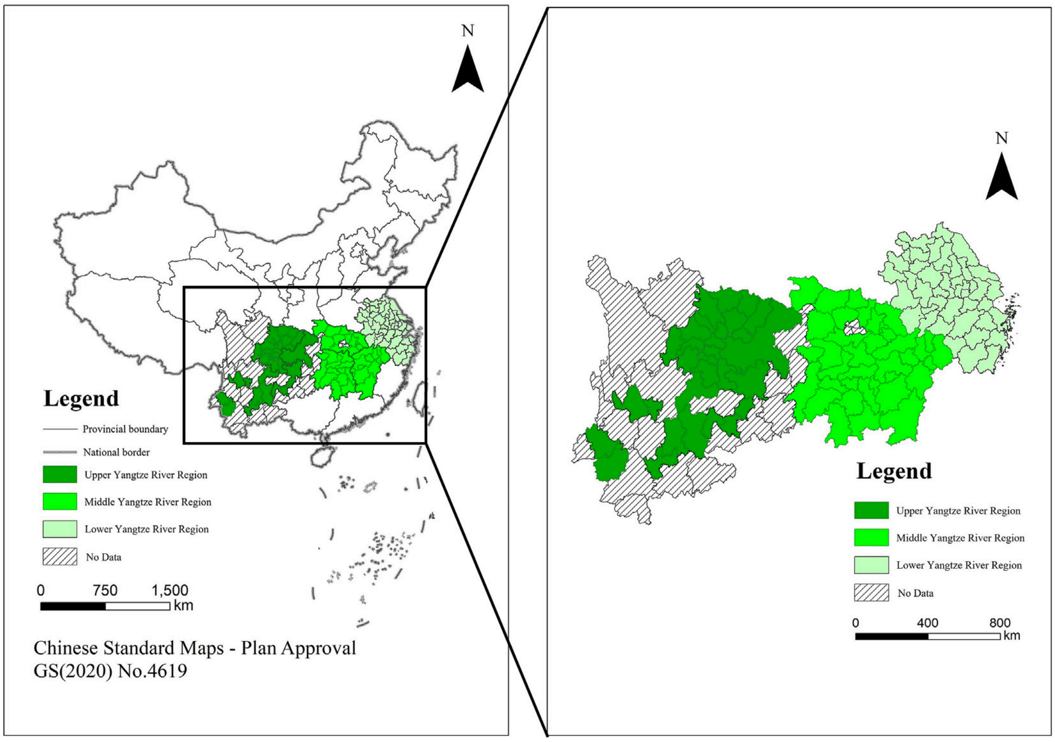

FIGURE 1
Study area.

TABLE 1 ULUE index system.

Type	Variable	Meaning	Unit	Reference
Input indicators	Land	Urban construction land area	km^2	Chen et al. (2022); Lu et al. (2022); Wang et al. (2022); Yang et al. (2022)
	Capital	Investment in fixed assets	CNY 100 million	
	Labor	Number of employees in secondary and tertiary industries	10,000 persons	
	Resource	Total urban water supply	10,000 tons	
Desirable output indicators	Economic benefit	Gross product of second and tertiary industries	CNY 100 million	
	Social benefit	Per capita disposable income of urban residents	CNY	
	Environmental benefit	Green coverage of built-up area	%	
Undesirable output indicators	Carbon emission	Carbon emission	10,000 tons	

investment in fixed assets is chosen as the index of capital input in this study. ③Labor input. Labor force is an important subject to promote the process of urban land use (Xiao et al., 2022), and the industries in the city are mainly secondary and tertiary industries, so this study selects the number of employees in secondary and tertiary industries as the capital input index. ④Resource input. The process of urban land development consumes a large amount of resources, and urban water supply is the lifeline of cities and an indispensable component of urban land use (Zhang et al., 2022). Therefore, the total urban water supply is chosen to represent the resource input in this paper.

(2) Desirable output indicators: ①Economic benefits. Economic benefits are the most important and measurable output of urban land use, and the development of cities mainly relies on secondary and tertiary industries (Song et al., 2021). So this study selects the output value of secondary and tertiary industries to represent the economic output benefit indicators of land use.

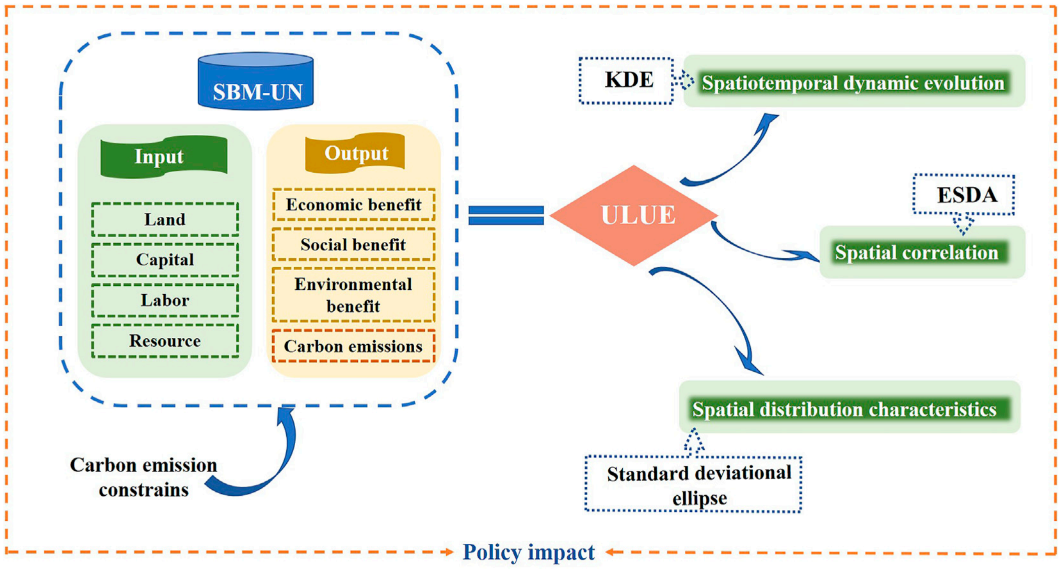

FIGURE 2
Workflow chart of ULUE research in the YREB.

②Social benefits. The social benefits of ULUE are mainly reflected in the improvement of residents' social level and quality of life (Li et al., 2014), and the disposable income of urban residents is used to represent the social benefits of urban land use output according to people's good wishes. ③Environmental benefits. Environmental benefits reflect the environmental friendliness of urban land use, and green areas are conducive to increasing urban ecological diversity and improving ecological environment (Lu et al., 2022), so the greening coverage of urban built-up areas is chosen to represent the environmental expectation output.

(3) Undesirable output indicators: carbon dioxide is a direct manifestation of the negative externalities of urban economic activities on the environment (Lu et al., 2022), so this paper measures the total land use carbon emissions of each city by adding up the carbon emissions generated from electricity, gas and LPG, IPCC2006 emission coefficient is used to calculate the CO_2 emissions of direct energy such as natural gas and liquefied petroleum gas. For the CO_2 consumed by electricity, due to its complexity, referring to the calculation method of power CO_2 emissions of (Wu and Guo, 2016) and (Zeng et al., 2022), that is, the power grid of each region uses the emission coefficient of the corresponding region, and the CO_2 emissions generated by electricity use in the YREB can be calculated according to the baseline emission coefficient of the power grid of the region over the years and the electricity consumption of each region. The calculation formula of CO_2 emissions is shown in the follow equation:

$$CO_2 = \sum_{i=1}^{n} CE_i = \sum_{i=1}^{n} E_i{*}EF_i \tag{1}$$

CO_2 represents the sum of CO_2 emissions generated by multiple energy resources; CE_i represents the CO_2 emissions of the i-th energy resources, and n represents the type of energy; E_i represents the consumption of energy i, and EF_i represents the emission factor of energy i.

3.2.2 Data source

This study analyzes the ULUE of 107 cities in the YREB of China. The data required in this paper are obtained from public information sources such as the China Urban Statistical Yearbook, China Urban Construction Statistical Yearbook, China Energy Statistical Yearbook and the statistical yearbooks of provinces and cities from 2006 to 2020, and the few missing data are estimated by linear interpolation.

3.3 Research methods

In order to effectively measure the ULUE level of the YREB and demonstrate its spatio-temporal evolution characteristics, SBM-UN, KDE, ESDA, Standard evolutionary ellipse are used in the study, as shown in Figure 2 below:

3.3.1 SBM-UN model

DEA, which is a non-parametric frontier approach, has become a mainstream technical tool for assessing efficiency due to its many advantages such as no prior determination of functional relationships, non-subjective weighting, and reduced bias in efficiency measurement. The traditional DEA model doesn't consider input or output slack, so Tone (2001) proposed a slack-based measure (SBM) model based on non-radial and non-angular, which integrates the input and output of each decision-making unit, and put slack variables directly into the objective function, thus solving the problem of input-output slack. However, undesirable outputs such as the negative impact of urban land use on the environment are not considered. Based on this, we adopt the SBM-UN model, which takes into account the unexpected outputs, so as to measure the ULUE of the YREB under the dual constraints of energy and environment more accurately.

The principle is as follows: each city is considered as a Decision Making Unit (DMU), and each DMU has an input vector, denoted as $x \in Rm$ and two output vectors: desired and undesired outputs, denoted as $Yg \in Rs1$ and $yb \in Rs2$. Define the following matrix: $X = [x1, x2, \cdots, xn] \in Rm\times n$, $Yg = [y1g, y2g, \cdots, yng] \in Rs1\times n$, $Yb = [y1b, y2b, \cdots, ynb] \in Rs2\times n$. Based on the input and output realities, assuming $xi > 0$, $yig > 0$, $yib > 0$, the set of production possibilities p, i.e., all combinations of desired and undesired outputs produced by N factor inputs x, can be defined as:

$$P = \left\{ \left(x, y^g, y^b\right) \middle| x \geq X\lambda,\ y^g \geq Y^g\lambda,\ y^b \geq Y^b\lambda,\ (\lambda \geq 0) \right\} \tag{2}$$

According to this definition, the SBM-UN model is defined as follows.

$$\rho^* = min \frac{1 - \frac{1}{m}\sum_{i=1}^{m} \frac{S_i^-}{X_{i0}}}{1 + \frac{1}{S_1+S_2}\left(\sum_{r=1}^{S_1} \frac{S_r^g}{y_{r_0}^g} + \sum_{r=1}^{S_2} \frac{S_r^b}{y_{r_0}^b}\right)} \tag{3}$$

$$s.t. \begin{cases} X_0 = X\lambda + S^- \\ y_0^g = Y^g\lambda + S^g \\ y_0^b = Y^b\lambda + S^b \\ S^- \geq 0, S^g \geq 0, S^b \geq 0, \lambda \geq 0 \end{cases} \tag{4}$$

In Eqs 3, 4, S_i^-, S_r^g and S_r^b denote the input redundancy, desired output shortage and undesired output overrun of the i_0th decision unit, respectively, and S^-, S^g, and S^b are their corresponding vectors; λ is the weight vector. The objective function ρ^* is strictly decreasing with respect to S_i^-, S_r^g, and S_r^b, and $0 \leq \rho^* \leq 1$. For a particular evaluated unit: 1) it is efficient when $\rho^* = 1$, i.e., when S_i^-, S_r^g, and S_r^b are all 0; 2) it is inefficient when $0 \leq \rho^* < 1$, i.e., when at least one of S_i^-, S_r^g, and S_r^b is not 0, and there is a need for input-output improvement. Also, since the model is a non-linear programming model, it is usually solved by transforming it into a linear programming model using the conversion method of Charnes et al. (1978).

3.3.2 Kernel density estimation (KDE)

Kernel density estimation is a non-parametric method for estimating probability density function of random variables with kernel as weight. It can intuitively describe the time dynamic evolution characteristics of variables, and can also avoid errors caused by improper assumptions about the data form, thus making the estimation results more fitting and robust (Tan et al., 2021). Considering this advantage, combined with the data type and content of this study, it is feasible to use kernel density estimation to characterize urban land use efficiency in the YREB. Therefore, this paper uses the ULUE value to analyze the dynamic distribution characteristics of ULUE in the Yangtze River Economic Belt in 2006, 2009, 2012, 2015, 2018, and 2020 from the overall and three major regions (upstream, midstream, and downstream). The formula is as follows.

$$f(x) = \frac{1}{nh}\sum_{i=1}^{n} K\left(\frac{x - x_i}{h}\right) \tag{5}$$

In Eq. 5: n is the sample size, h is the bandwidth, $K(\cdot)$ is the kernel function, x_i is the observed value, and x is the mean value of the observed value. In order to ensure the reasonableness of the KDE estimation results, the kernel function should satisfy $K(x) \geq 0, \int_{-\infty}^{+\infty} k(x)dx = 1$. According to the different expression forms, the kernel function can be divided into triangular kernel, quadratic kernel, and Gaussian kernel. When the amount of grouped data is low, the Gaussian kernel function is more accurate than other forms of functions. Therefore, in this paper, the Gaussian kernel function is used for estimation, and the formula is as follows.

$$f(x) = \frac{1}{\sqrt{2\pi}}\exp\left(-\frac{x^2}{2}\right) \tag{6}$$

3.3.3 Exploratory spatial data analysis (ESDA)

Exploratory spatial data analysis (ESDA) method is a collection of spatial data analysis techniques and methods. It is used to describe the spatial distribution patterns of data and represent them visually, identify outliers in spatial data, detect the spatial clustering effects of certain phenomena, explore the spatial structure of data, and reveal the spatial interaction mechanisms between phenomena (Messner et al., 1999). Spatial autocorrelation analysis is one of the core elements of ESDA technique and is often performed by Moran's I. Moran's I is further divided into global Moran's I and local Moran's I. The global Moran's I is used to evaluate whether the ULUE level is relevant or random. If I value is greater than 0, the ULUE level is positively correlated in space; If I value is less than 0, ULUE level is negatively correlated in space; If I value is equal to 0, it is a random distribution. In addition, the study uses the local Moran's I to reveal whether there is a significant difference between the ULUE level of a region and its surrounding ULUE levels, to analyze the local agglomeration characteristics of the ULUE level of the YREB, and thus obtain the cold and hot spots of the ULUE level. The specific formula is as follows.

(1) Global Moran's I

$$MI = \frac{n \times \sum_{i=1}^{n}\sum_{j\neq 1}^{n} W_{ij}(x_i - \bar{x})(x_j - \bar{x})}{\left(\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}\right) \times \sum_{i=1}^{n}(x_i - \bar{x})^2} \tag{7}$$

In Eq. 7, MI denotes Moran's I; n represents the number of cities; x_i and x_j denote the observed values in cities i and j; $\bar{x}$ denotes the mean value; W_{ij} denotes the weights of spatial units i and j. When i and j are adjacent, $W_{ij} = 1$, and *vice versa* is 0.

The significance level of Moran's I was tested with the statistic Z.

$$Z(MI) = \frac{1 - E(MI)}{\sqrt{Var(MI)}} \tag{8}$$

In Eq. 8: $E(MI)$ is the theoretical value; $Var(MI)$ is the theoretical variance. When $Z(MI)$ is positive and significant, it indicates that there is a positive spatial autocorrelation in the region.

(2) Local Moran's I

$$MI_i = \frac{n(x_i - \bar{x})\sum_{j=1}^{m} W_{ij}\left(x_j - \bar{x}\right)}{\sum_{j=1}^{n}\left(x_j - \bar{x}\right)^2} \tag{9}$$

In Eq. 9, x_i and x_j denote the observed values in cities i and j; n represents the number of cities; $\bar{x}$ denotes the average value; W_{ij} denotes the weight of spatial units i and j; m is the number of cities geographically adjacent to city i. $MI_i > 0$ indicates the proximity of areas with the same type of element attribute values (H-H or L-L); $MI_i < 0$ indicates the proximity of areas with different type of element attribute values (L-H or H-L). The greater the absolute value of this index value, the greater the degree of proximity.

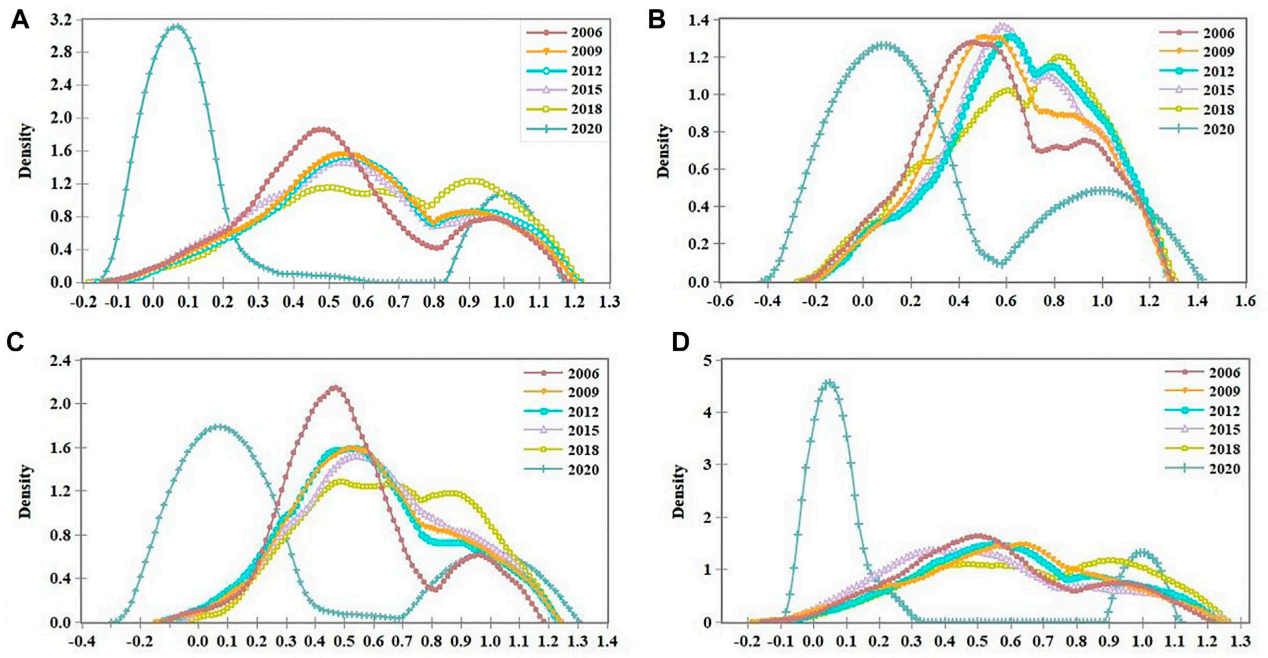

FIGURE 3
Kernel density distribution of ULUE in the YREB, **(A)** The whole YREB, **(B)** The upstream area, **(C)** The midstream area, **(D)** The downstream area.

3.3.4 Standard deviational ellipse

The standard deviational ellipse model is an analytical method proposed by Lefever (1926) to precisely portray the spatial distribution characteristics of the study object, which mainly includes the basic elements such as center of gravity, long and short axes, and azimuth. The center of gravity represents the main spatial location of the elements, which usually coincides roughly with the location of the arithmetic mean. The long axis indicates the direction of data distribution, while the short axis indicates the range of data distribution. The azimuth reflects the trend direction of the distribution of the study object. This paper applies this method to present the distribution pattern and evolution of ULUE in the YREB, as follows.

(1) Center of gravity coordinates

$$p_i(x_j, y_j) = \left[\frac{\sum_{i=1}^{n} w_i x_i}{\sum_{i=1}^{n} w_i}, \frac{\sum_{i=1}^{n} w_i y_i}{\sum_{i=1}^{n} w_i}\right] \quad (10)$$

(2) Azimuth

$$tan\,\theta = \frac{\left(\sum_{i=1}^{n} w_i^2 x_i'^2 - \sum_{i=1}^{n} w_i^2 y_i'^2\right) + \sqrt{\left(\sum_{i=1}^{n} w_i^2 x_i'^2 - \sum_{i=1}^{n} w_i^2 y_i'^2\right) + 4\left(\sum_{i=1}^{n} w^2 x_i'^2 y_i'^2\right)^2}}{2\sum_{i=1}^{n} w_i^2 x_i' y_i'} \quad (11)$$

(3) x-axis standard deviation, y-axis standard deviation

x-axis standard deviation:

$$\sigma_x = \frac{\sqrt{\sum_{i=1}^{n} \left(w_i \overline{x_i} \cos\theta - w_i \overline{y_i} \sin\theta\right)}}{\sum_{i=1}^{n} w_i^2} \quad (12)$$

y-axis standard deviation:

$$\sigma_y = \frac{\sqrt{\sum_{i=1}^{n} \left(w_i \overline{x_i} \sin\theta - w_i \overline{y_i} \cos\theta\right)}}{\sum_{i=1}^{n} w_i^2} \quad (13)$$

where (x_i, y_i) is the spatial location of the study object; w_i is the weight; i is each decision unit; x and y denote the relative coordinates of each point from the center of the region, respectively; $tan\,\theta$ can get the turning angle of the distribution pattern.

4 Results

4.1 Distribution dynamics of ULUE in the YREB

Figure 3A shows the ULUE kernel density curve of the whole YREB in 2006, 2009, 2012, 2015, 2018, and 2020. It can be seen from the shape that during the study period, the ULUE of YREB is basically double peaked, with the main peak on the left and the secondary peak on the right. It means that more regions are concentrated at the middle and low levels, while a few regions are concentrated at the high levels. In terms of location, from 2006 to 2018, the peaks were similar, with a slight downward trend, and mainly concentrated in the area of .5 on the right side of the X-axis. In 2020, the peak shifted significantly to the left, the main peak increased significantly, and the level of ULUE decreased significantly. From the point of distribution form, from 2006 to 2018, the distribution was "flat" with a large gap between regions. ULUE was mostly at a medium level and showed a slow upward trend. The possible reason is that the 18th National Congress of the Communist Party of China has integrated the concept of ecological civilization into urban construction and promoted the coordinated development of social and economic development and environmental protection, thus optimizing

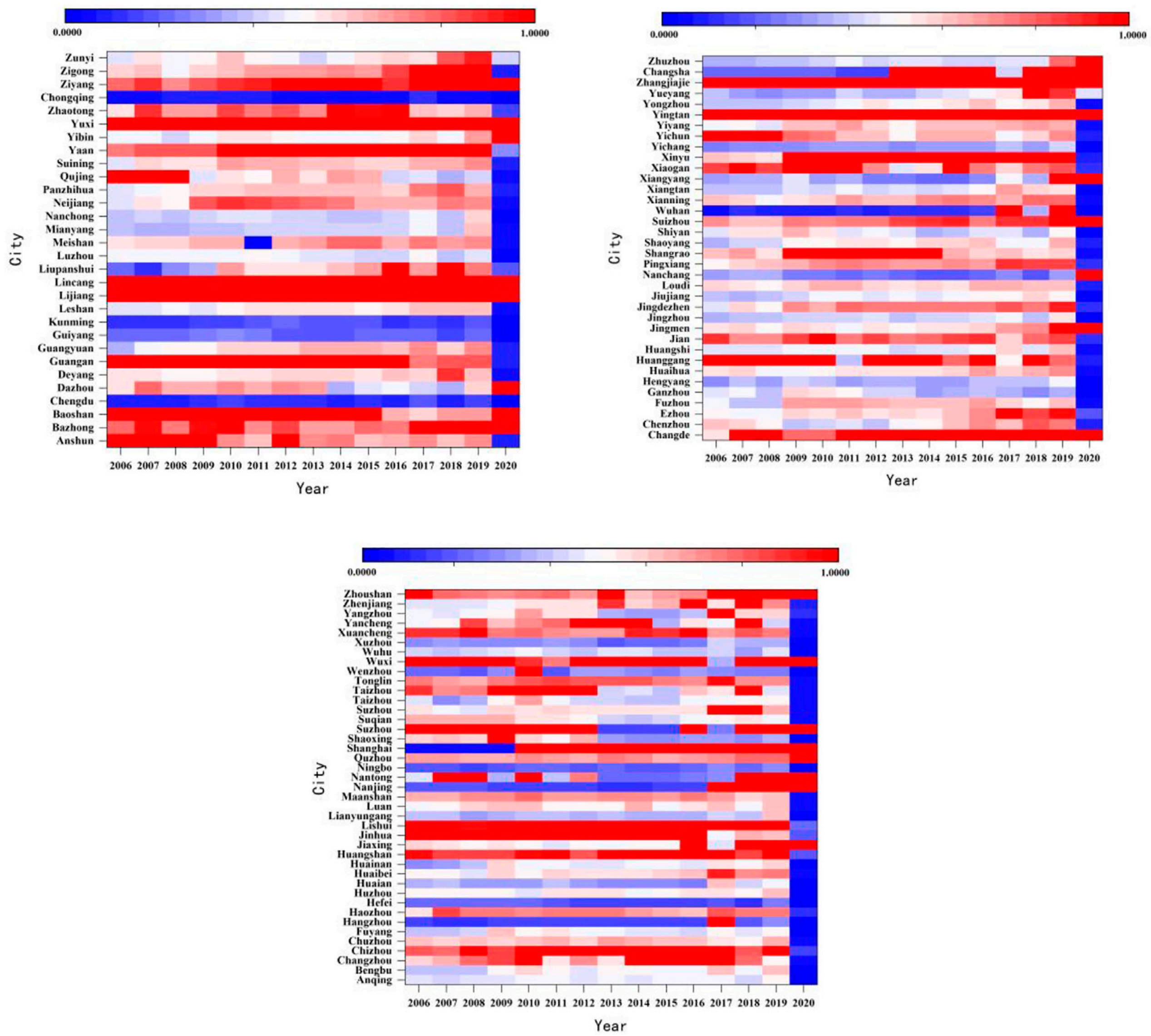

FIGURE 4
The hot spot maps of ULUE in the YREB.

urban industrial institutions and improving the efficiency of urban land use. In 2020, the gap between the two peaks widened, and the regional gap narrowed, but the level of ULUE significantly decreased. The width of the main peak changed from "slightly widened" to "substantially narrowed" in 2020, indicating that the regional difference of the overall ULUE in the YREB increased slightly from 2006 to 2018, and then narrowed rapidly. The level of ULUE was gradually dispersed but it is extremely sensitive to external changes. The epidemic caused ULUE to become concentrated.

Figures 3B–D, show the distribution dynamics of the upstream, midstream and downstream of the YREB. It can be seen that there are great differences in the kernel density curves of ULUE in the three regions. Specifically, the peak in the upstream of the YREB has experienced a process of shifting to the right first and then to the left. The ULUE first increased and then decreased. The peak height was relatively consistent, and the difference in the level of land use efficiency among cities in the upstream area was basically stable during the study period. The ULUE in the midstream also increased first and then decreased, but for the urban difference, there was a relatively obvious fluctuation in the midstream, and the difference between cities first expanded and then gradually narrowed. In the downstream, the change was relatively stable from 2006 to 2018. With the peak slowly moving to the right and gradually decreasing, the gap of ULUE between cities was widening, but the efficiency value showed an upward trend. However, in 2020, the peak shifted to the left and significantly increased, and the efficiency value decreased, and the urban difference was sharply reduced.

4.2 ULUE temporal evolution analysis of the YREB

In order to more clearly observe the change trend of ULUE in each city from 2006 to 2020, the ULUE hotspot maps of 107 cities in the study sample from 2006 to 2020 were drawn (Figure 4). As can be seen from the

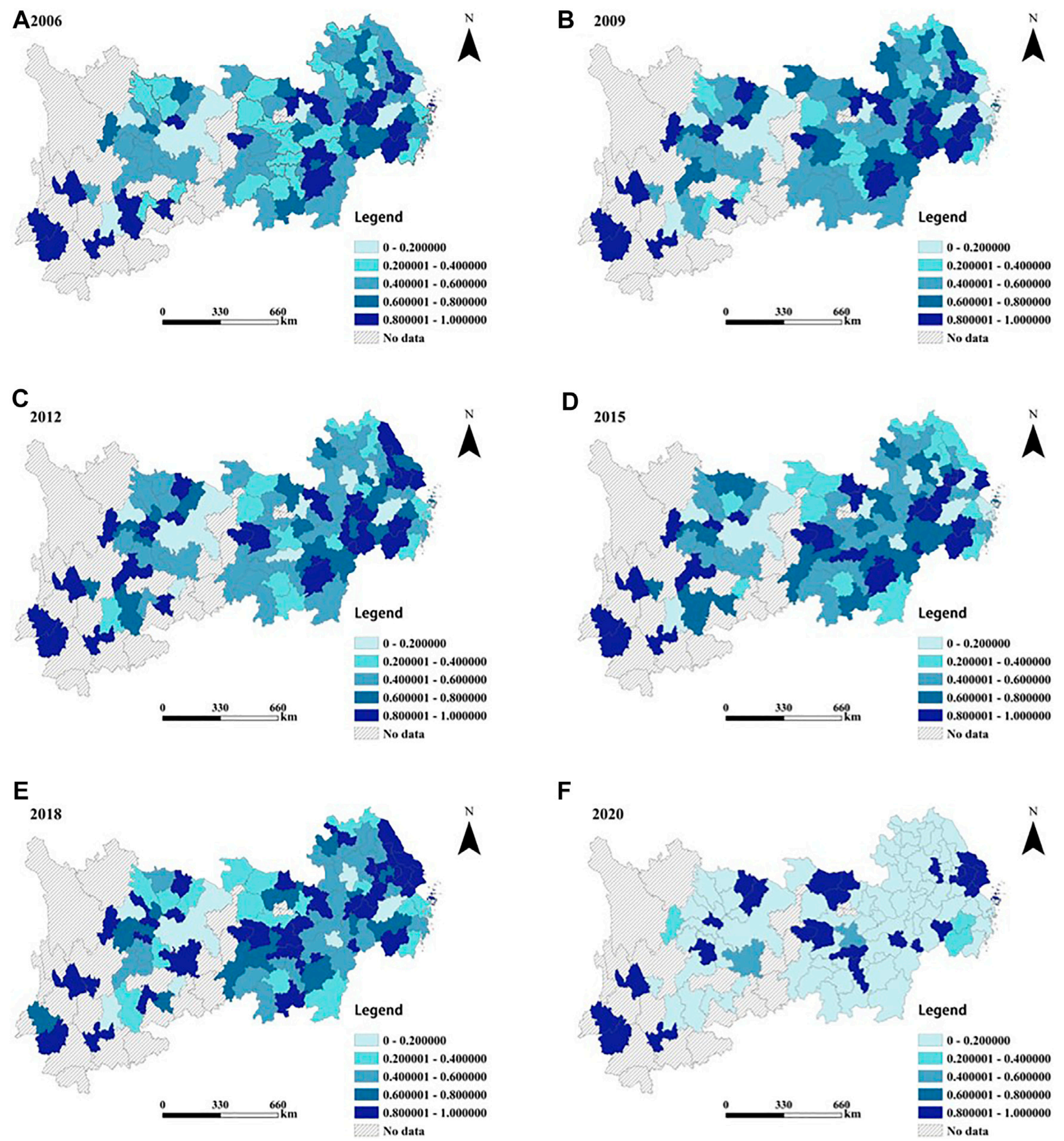

FIGURE 5
Evolution of ULUE in the YREB **(A–F)** represents the ULUE levels of the YREB in 2006, 2009, 2012, 5015, 2018, and 2020, respectively.

figures, the relatively shallow color blocks accounted for a large proportion, indicating that the ULUE of most cities in the YREB was at a medium level of about .3–.7 during the study period. With the proposal of the development strategy of the YREB, various regions actively promote the optimization and upgrading of the urban industrial structure, and the level of ULUE fluctuates and rises over time, and then drops sharply in 2020. ULUE in most cities, except Lincang, Lijiang, Dazhou, Baoshan, Bazhong, Zhoushan, Wuhu, Shanghai, Changsha, Zhangjiajie, and so on, all dropped below .2 in 2020. For example, Wuhan began to improve gradually after a long period of low efficiency, and its ULUE reached 1 in 2019, while it was less than .1 in 2020. This may be mainly due to the impact of the COVID-19 epidemic, which made the developed land resources unable to play an effective value. In 2020, the sudden COVID-19 hit the social and economic development of many cities represented by Wuhan heavily, making the land, human resources, capital and other resources not effectively used, and reducing the output of economic and social benefits, thus greatly reducing the efficiency of land use. This also warns relevant departments to strengthen their ability to deal with sudden crises, improve predictability, adapt to the situation and formulate reasonable countermeasures.

4.3 Analysis of ULUE spatial distribution in the YREB

4.3.1 Spatial distribution pattern of ULUE in the YREB

In this study, ULUE in the YREB were equally divided into five categories, and visualized by ArcGIS software (Figures 5A–F). As can be seen from the figure, from 2006 to 2018, cities with ULUE higher

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TABLE 2 ULUE global Moran's I value of the YREB.

Year	M'I	P	Z	Year	M'I	P	Z
2006	−0.08872	0.20107	−1.2785	**2014**	−0.0090	0.0069	0.9945
2007	−0.05664	0.44696	−0.7605	**2015**	−0.0026	0.10942	0.91287
2008	−0.03652	0.66246	−0.4365	**2016**	0.02658	0.58010	0.56184
2009	−0.03709	0.65579	−0.4457	**2017**	−0.0091	0.00541	0.99569
2010	0.109241	1.91214	0.05586	**2018**	0.08239	1.47783	0.13946
2011	0.02294	0.52219	0.60153	**2019**	0.07829	1.41508	0.15705
2012	0.07565	1.37082	0.17043	**2020**	0.13896	2.39410	0.01666
2013	−0.02374	−0.2305	0.81774				

than .8 and lower than .2 were scattered and interlaced in the upstream, midstream and downstream areas, which indicated that the overall level of ULUE in the three areas was relatively balanced. Cities with efficiency values less than .2 are mainly distributed in the upstream and downstream, and only Changsha and Wuhan have efficiency values less than .2 in the midstream. The polarization phenomenon in the midstream is relatively the weakest. Provincial capital cities, such as Changsha, Hefei, Nanjing, Nanchang, Guiyang, Kunming and other places, generally had ULUE in the level range of 0–.2 and .2–.4. Provincial capital cities are political, economic and cultural centers and key areas for development. However, in the process of development, disorder and excess lead to serious waste of resources, which leads to low ULUE level. In 2020, ULUE levels were generally low, mainly due to the impact of COVID-19.

4.3.2 Spatial correlation of ULUE in the YREB

In order to explore the spatial correlation of ULUE in the YREB, ArcGIS was used to calculate the global Moran's I (Table 2). It can be found that in 15 years, the value of the Moran's I showed staggered distribution of positive and negative phases, and none of them was 0. However, only the Moran's I in 2010 and 2020 passed the significance test, and the other years failed. It indicates that there was no significant interaction and spillover effect between ULUE of a city and ULUE of neighboring cities in the YREB except in 2010 and 2020, and the spatial relationship was randomly distributed. The correlations between 2010 and 2020 were significant at the level of 5%, and both were positive, indicating that ULUE in the YREB had positive spatial correlation in these 2 years.

Based on the above-mentioned global spatial autocorrelation analysis, we can only see the global spatial correlation characteristics of ULUE in the YREB. In order to further explore and analyze the local spatial pattern of ULUE, and identify the four agglomeration modes of high-high (H-H), low-low (L-L), high-low (H-L), and low-high (L-H) in 107 samples studied in the YREB, the study used ArcGIS to draw local spatial agglomeration maps of ULUE in the YREB in 2006, 2009, 2012, 2015, 2018, and 2020 (Figure 6). In 2006, only H-L and L-H agglomeration modes existed in the study area, which were respectively distributed in Chuzhou, Anshun, Qujing, Yuxi, Panzhihua, Kunming, Liupanshui, Anqing, Hangzhou, Shanghai, and Wenzhou. From 2009 to 2018, H-L and L-H areas were reduced, and some H-H and L-L clustering areas appeared in Shanghai, Quzhou, Xianning, Suqian, etc. The clustering areas were unstable and constantly changing over time. In 2020, the number of agglomeration areas increased significantly, with L-H agglomeration accounting for the largest proportion. In general, the local spatial correlation of ULUE in the YREB was characterized by "small aggregation range and unstable location." In 2020, a large range of L-L agglomeration areas appeared in the northeast of the YREB. In the subsequent development of these cities, the use of urban construction land should be strictly controlled, and the ability to resist risks should be improved to promote their transformation to H-H agglomeration.

4.4 ULUE spatial trajectory analysis in the YREB

In this study, ArcGIS10.6 was used to make the ULUE standard deviation elliptic graph of the YREB in 2006, 2009, 2012, 2015, 2018, and 2020 (Figure 7), from which it can be seen that the long axis was always larger than the short axis, showing an obvious distribution pattern of "northeast-southwest." To be specific, the azimuth θ of ULUE in the YREB was always around 72° and 73°, and the variation range was less than 1°, which indicated that the center of gravity of ULUE in the YREB was relatively stable, and it basically moved around a straight line. During the study period, the distribution range of standard deviation ellipse showed a trend of decreasing fluctuation, and tended to be concentrated in spatial distribution. The fluctuation of the long axis increased, while the short axis gradually decreased, and the north-south direction gradually tended to be balanced.

From the perspective of the distribution of the center of gravity, from 2006 to 2020, the center of gravity was always located in Jingzhou, with a slight deviation during the period. The center of gravity reflects the spatial distribution center of the ULUE level. The shift of the center of gravity means that the urban land use efficiency has changed to varying degrees between regions. The shift of the center of gravity to the right means that the improvement degree of the right region is higher than that of the left region. The moving path can be roughly divided into four stages: the first stage was from 2006 to 2009, when the center of gravity shifted slightly to the north, with a moving distance of about 7.9 km; In the second stage, the center of gravity shifted about 40.3 km to the southwest from 2009 to 2015; The third stage is from 2015 to 2018, with the center of gravity shifting about 60.8 km to the northeast; In the fourth stage, from 2018 to 2020, the

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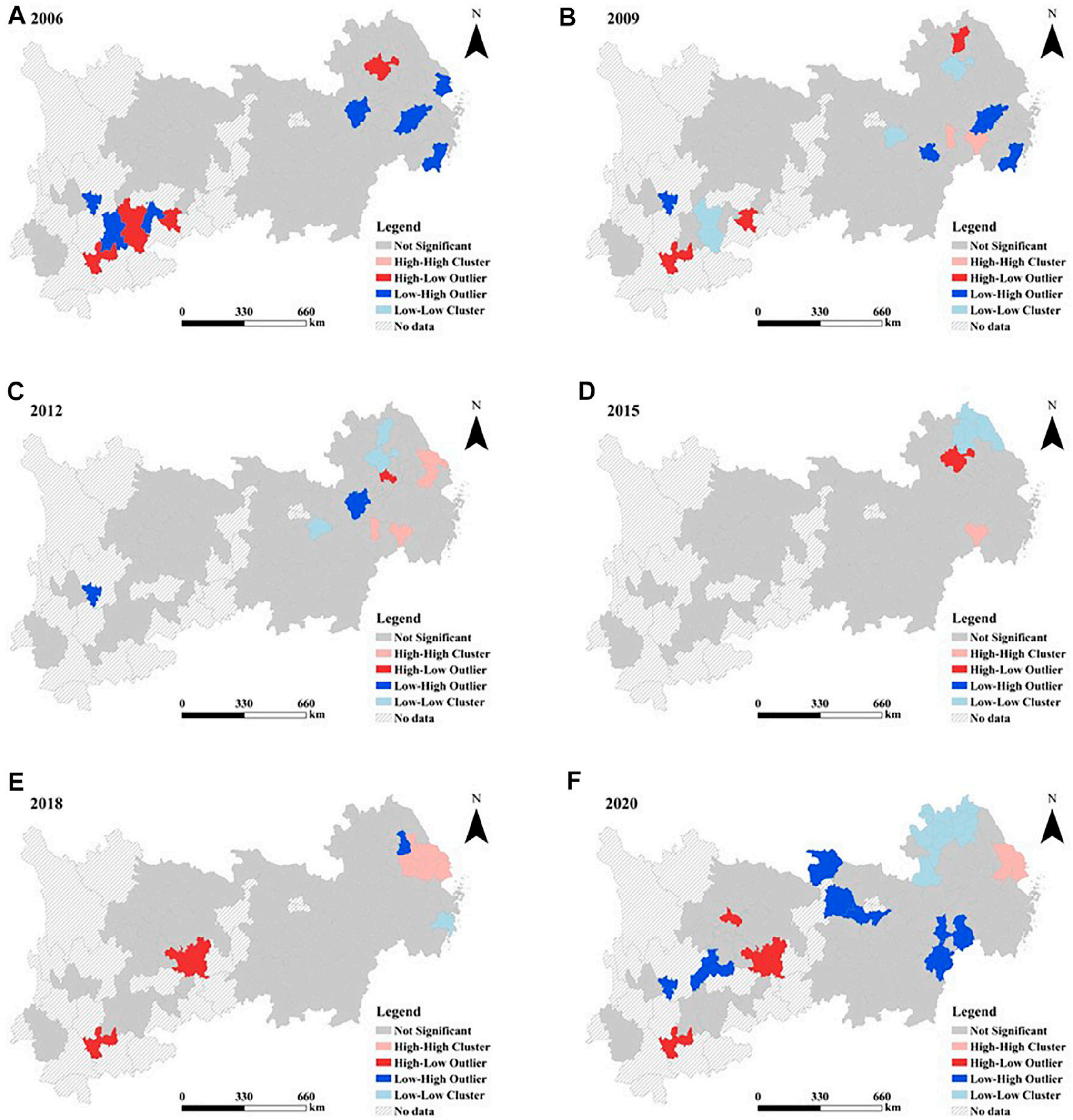

FIGURE 6
Local spatial agglomeration map of ULUE in the YREB **(A–F)** represents the local correlation of ULUE of YREB in 2006, 2009, 2012, 2015, 2018, and 2020, respectively.

center of gravity shifted to the southwest by a large margin, with an offset distance of 77.7 km. The shift direction of the center of gravity was extremely unstable during the study period, which indicated that the improvement amplitude of ULUE level in the YREB was quite different. For example, from 2006 to 2009, the improvement increment of ULUE in the northeast region was slightly larger than that in the southwest region, while from 2018 to 2020, the improvement increment of ULUE in the southwest region was significantly higher than that in the northeast region. On the whole, the ULUE center of gravity in the YREB shifted to the southwest during 2006–2020, and finally shifted to the southwest by about 52.7 km, indicating that the ULUE level of southwestern cities in the YREB was generally in a state of improvement. The reason may be that many cities in southwest China, such as Kunming and Lijiang, have unique natural and cultural advantages. For example, Yulong Snow Mountain in Lijiang and Kunming, which is known as the "Spring City," etc. In recent years, relying on these advantages, they have vigorously developed tourism, which not only reduces the dependence of urban development on construction land investment, but also attracts a large number of tourists, significantly increasing the regional GDP. At the same time, the tourism industry is widely considered as a "smokeless industry," with relatively low environmental pressure. All of the above have improved the level of ULUE.

5 Discussion

ULUE reflects the balance of economy, society and environment in the process of realizing land use, and plays a key role in achieving the

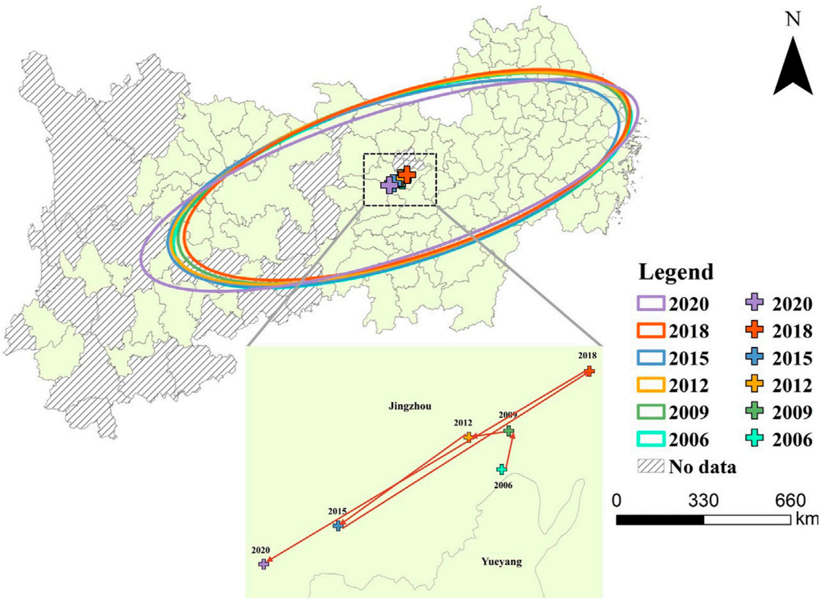

FIGURE 7
Diagram of standard deviation ellipse and center of gravity trajectory of ULUE in the YREB.

sustainable development goals of the land sector (Gao et al., 2017). When formulating land use policies, it is encouraged to choose different development models according to different environments and development levels in different regions (Sun et al., 2018), and adjust and optimize specific implementation policies over time (Bryan et al., 2018). Therefore, this study compared and analyzed the ULUE of different regions in recent 15 years, to help each region reasonably analyze its advantages and disadvantages, and according to historical experience, formulate ULUE promotion strategies that conform to the actual situation of the region, and ultimately achieve the sustainable development of the whole region.

First of all, in terms of calculation method, this study uses SBM-UN model considering unexpected output, which is different from the previous literature that used SFA or traditional DEA model to calculate ULUE (Cui et al., 2019; Lu et al., 2022). At the same time, in the selection of indicators, this study includes the negative externalities generated in the process of urban land use into the evaluation system, measure the efficiency of urban land use under the constraint of carbon emissions, and regard carbon emissions as unexpected output, so that the evaluation results are more comprehensive and accurate.

Second, from the perspective of development level, the ULUE of most cities in the YREB from 2006 to 2020 was at a medium level. It is worth noting that most cities generally have low ULUE levels in 2020, which may be affected by the impact of the COVID-19 break. Cities have always been the center of the COVID-19 outbreak (Sharifi & Khavarian-Garmsir, 2020). In order to prevent and control the COVID-19 epidemic, countries have increased the restrictions on population mobility, which has severely affected the secondary and tertiary industries, resulting in short-term basic stagnation of manufacturing and infrastructure investment, reduced GDP and increased unemployment rate. The impact on urban land use is huge (Corazza et al., 2021). Therefore, how to correctly deal with the impact of public crisis events on urban land use and management is particularly important for the future sustainable development of cities.

Thirdly, from the perspective of spatial pattern, there are great differences in the land use efficiency of cities in the YREB, and more cities are at the medium level of efficiency. In previous studies, Lu et al. (2022) found that the ULUE of the three major urban agglomerations in China kept improving, but there was obvious spatial imbalance. This finding is similar to the results of this study. Therefore, the implementation of regional coordinated development is an effective measure to improve the efficiency of urban land use in the YREB, which is consistent with the new regionalism principle of promoting regional integration and coordinated development proposed by Ethier (1998). In addition, we found that the provincial capitals, such as Hefei, Nanjing, and Guiyang, are generally located in the low level of ULUE. However, Yang et al. (2022) found that a high level of economic development was correlated with ULUE. The ULUE of central cities in the Yangtze River Delta in China remained high throughout the study period, which was contrary to the results of this study. The reason may be that the disorderly and excessive development of provincial capitals leads to the waste of resources and serious environmental pollution, which leads to the low level of ULUE. This proves that the land use of each city is different, so we believe that local governments can optimize the land use mode according to local conditions.

Based on the above analysis, this study proposed the following suggestions for policymakers to take transformative action.

Firstly, the government needs to consider the impact of public crisis events when planning urban land. For example, facilities such as parks, water bodies and emergency shelters can be added, and multi-level decentralized treatment of urban open space can be considered. We should be cautious about the development of high-rise modular building projects and moderately control the capacity of high-density residential areas. The impact on vulnerable areas and groups should be avoided or reduced in advance by making full use of space for time.

Secondly, rationally control the expansion scale of urban land and promote the intensive use of urban land. The rapid expansion of urban built-up areas will inhibit the efficiency of urban land use. Therefore, the central government should make an overall plan to control the scale of big cities in the YREB, reasonably develop medium cities and actively develop small towns (Mengbai, 1987). All regions should actively optimize the land use structure, ensure urban green space, reduce land used by high-pollution industries, and increase the proportion of land used for tertiary and high-tech industries.

Finally, break through the administrative barrier boundary and implement the regional urban land use coordinated development strategy. According to the previous analysis, the spatial spillover and interaction effect of ULUE in the YREB are not strong, which directly lead to the spatial imbalance of ULUE in the YREB. With the improvement of the transportation infrastructure, the central and the governments at all levels should take the YREB as a whole, and coordinate the layout of urban land use in the eastern, central and western regions, to break the administrative barriers and market boundaries, to promote the free flow of capital, technology, labor and efficient configuration, form downstream with the middle and upper middle belt pattern of land use efficiency.

6 Conclusion

In this paper, the SBM-UN model was used to measure the ULUE in the YREB from 2006 to 2020, and the spatial-temporal evolution trend was analyzed through kernel density and spatial autocorrelation calculation, etc., and the following conclusions were obtained: 1) ULUE varies greatly across the YREB. Since 2006, except for 2020, which showed a low level of low difference, ULUE showed an increasingly discrete trend, with the inter-city difference expanding slowly, and the overall level of ULUE increased slightly. The evolution dynamics of ULUE in the upstream, midstream and downstream were different. The density of ULUE was the highest in the median area, and the difference between cities was upstream > midstream > downstream, and the midstream was similar to the downstream, which had a great relationship with the most significant difference of urban development level in the upstream region. 2) Due to the COVID-19 epidemic, the ULUE level of most cities in the YREB decreased sharply in 2020, especially in large and medium-sized cities such as Changsha, Wuhan, and Nanjing. In addition, the ULUE level of all places showed a trend of fluctuation and rise from 2006 to 2018. 3) From the perspective of spatial distribution, the regional distribution of different levels of development was relatively scattered. What needs special attention is that the ULUE level of cities with high level of economic development, such as Chongqing, Chengdu, Kunming, and Guiyang, is relatively low. There were unreasonable input-output structure, resource waste and serious environmental pollution in these areas. 4) From the perspective of spatial correlation, the global spatial correlation was only significant in 2010 and 2020, but it was weak. The local spatial correlation showed a trend of weakening at first and then strengthening. The agglomeration areas were mainly concentrated in some upstream and downstream areas, and the scope of agglomeration area was small. On the whole, the spatial relationship of ULUE was relatively loose, and the spillover and interaction effects were weak. 5) From the point of space track, the standard deviation ellipse distribution gradually flattened, ULUE north-south difference abated, and the center of gravity moving trajectory was stable, but the direction was changeable, and eventually the southwest direction was substantially offset. Throughout the study period, southwest ULUE ascension increment was significantly higher than the northeast, further showing the level of urban development and structure optimization of ULUE boost.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

LP conceived and designed the study. QY completed the results analysis and summary. GG and XW were responsible for data collection and sorting, while CJ and GH calculated the collected data and made charts. HT checked the research manuscript and proposed amendments.

Funding

This research was financially supported by the National Natural Science Foundation of China (Grant No. 41871083; Grant No. 42171245).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 12 January 2023
DOI 10.3389/fenvs.2023.1115067

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OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to
Environmental Economics and
Management,
a section of the journal
Frontiers in Environmental Science

RECEIVED 03 December 2022
ACCEPTED 02 January 2023
PUBLISHED 12 January 2023

CITATION
Tang Z, Fu M, Wang Y and Zhao Y (2023),
Spatial characteristics of industrial
economic location and its formation in
Chongqing, China.
Front. Environ. Sci. 11:1115067.
doi: 10.3389/fenvs.2023.1115067

Spatial characteristics of industrial economic location and its formation in Chongqing, China

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As the core carrier and organizational bodies of the regional industrial space, the study of the location of industrial enterprises and the formation of their economic location is related to the rational development of regional industries, the coordination of humans and the environment, and the effective allocation of resources. Taking Chongqing, one of the six old industrial bases in China, as an example, this study analyzed the spatial distribution characteristics, economic location characteristics, and formation laws of industrial enterprises based on the Points of interest data (POI), and investigation data. The results showed that industrial enterprises in Chongqing show obvious spatial clustering characteristics. About 93.50%, 60.34%, 96.67%, 97.57%, 73.57%, 64.83% of industrial enterprises were distributed within the spatial range of 10 Km from the motorways, national highways, provincial highways, county highways, main streams of rivers and central towns, and 93.48% of industrial enterprises were distributed at an altitude of 800 m or less. In order to further reveale the economic location characteristics of industrial enterprises in Chongqing, this study further quantified the spatial differentiation law of industrial economic location based on Geographically weighted regression (GWR). The results showed that factors such as the Distance to National Highways (DNH), Distance to County Highways (DCH), Distance to Central Towns (DCC), Distance to River systems (DR), and Population Density (POP) had significant positive impacts on the formation of economic locations of industrial enterprises, while the Distance to Motorway (DMW) exerted a certain negative influence, but the effectiveness sees strong spatial heterogeneity according to the type of industry and the actual regional industrial development, with factors such as transportation accessibility, environment, and labor force playing a moderating role.

KEYWORDS

industrial location, economic location, spatial heterogeneity, GWR, Chongqing

1 Introduction

Industrial development is the main driving force of the regional economy. Research on the location characteristics and formation of industrial enterprises, the core carriers and organizing bodies of the regional industrial space, are concerned with the regional industrial spatial layout and effective resource allocation (Helsley, 2003; Ottaviano, 1999). Studies on the spatial distribution of industrial enterprises can be traced back to Ebenezer Howard's (1889) discussion about the layout of industrial land in cities in his theory of Garden City. Isard (1956) developed and constructed a research framework of industrial space, and started the research of regional science from the perspectives of the spatial layout of industry and the relationship between location and market. Regarding administrative units, the existing studies on the spatial distribution of industrial enterprises cover multiple levels including national, provincial, municipal, and urban agglomeration (Helsley, 2003; Mohan, 1997; Viladecans-Marsal, 2004; Peneder, 2015; Wang K. et al., 2020). In terms of industry, most of the research focuses on the overall study of the secondary industry, with studies relatively concentrated on single industrial categories or single enterprises such as heavy industry and chemical industry (Baykov, 2010; Ottaviano, 1999; Yong, 2012; Cheng et al., 2018; Wu et al., 2021). For instance, Wu conducted a study on the investment location differences and changing dynamics of Chinese chemical companies using the database of capacity investment of Chinese listed chemical companies, revealing the north-south differences in location choices of chemical companies whether it is State-owned or not (Wu et al., 2021). In terms of research methods, distance-based industrial agglomeration measurement methods such as DO index and M function, and quantitative identification methods of industrial clusters such as location entropy, factor analysis, and cluster analysis are widely used (Gu and Ding, 2022; Rikalovic, 2015; Spinola et al., 2015; Zeng et al., 2008).

The economic location characteristics presented by the spatial distribution of industrial enterprises have long been a research focus in the fields of industrial planning and regional planning. The economic location of an industrial enterprise is a choice made according to the principles of economics (Wu and Shi, 1997). The formation of industrial enterprises' economic locations is closely related to the comprehensive exploitation and utilization of natural, social, and economic resources. Currently, a variety of factors, including the economy, market, transportation, communication, policy, and physical geography are widely discussed in terms of the formation of the economic locations of industrial enterprises (Nguyen and Diez, 2017; Pe'Er and Vertinsky, 2006; Renfeng et al., 2018; Sun et al., 2014; Zhang et al., 2021). For example, Aviad Pe'er (Pe'Er and Vertinsky, 2006) discussed the influence of location characteristics, such as agglomeration, competition, deterrence, and sunk costs, on location choices Using data about all *de novo* entrants into the Canadian manufacturing sectors during 1984-1998, revealing the preference characteristics of location choice of different enterprises. At the same time, Sun et al. (2014) portrayed the preference characteristics of various types of enterprises in Shenyang for public facilities and water conservancy facilities in their economic location choice through a potential model. Regarding research methods, quantitative analysis methods such as ordinal categorical logistic regression models and SLM are also widely adopted. However, due to the limitations of analysis methods and data of industrial enterprises, the current research on the economic locations of industrial enterprises is mostly focused on single industries or single enterprises, with a dearth of in-depth studies on industrial enterprises in general within certain administrative units and functional units. As a result, it is difficult to obtain reliable conclusions that can reflect the overall regional development, thus making it hard to provide valuable references for the industrial development of the regions, which to a certain extent, also restricts the development of the economic location theory. The advancing big data and spatial information technology can bridge this gap in some ways, but there have been few similar attempts in the research on industrial economic location.

Therefore, this study took Chongqing, one of China's six old industrial bases, as an example, and carried out a study of the economic locations of industrial enterprises within the city based on POI, API. As the only municipality directly under the central government in Western China, Chongqing witnessed rapid industrial development in the early years due to its advantageous water transport conditions. With the transformation of China's economic structure in recent years, however, the spatial contradiction between its economic development and ecological protection has intensified and the livelihood, economic, and environmental problems caused by factors such as poor topographical conditions, simplistic industrial structure, and unreasonable industrial layout have gradually stood out. Hence, it is of great practical significance to explore the spatial distribution and economic location characteristics of industrial enterprises in Chongqing at the spatial level and understand the laws of the formation of the economic locations for formulating reasonable industrial spatial planning, guiding industrial development, and alleviating urban problems.

2 Materials and methods

2.1 Study area and data preparation

Chongqing, also known as Mountain City, is located in southwest China (Figure 1). It is the economic center of the upper reaches of the Yangtze River, the financial center of Western China, and an important national center for advanced manufacturing. In addition, it is the only municipality directly under the central government in Western China and one of the cores in constructing the Chengdu-Chongqing economic circle. Chongqing covers an area of 82,400 square kilometers. It has 26 districts and 12 counties, of which Yuzhong District, Dadukou District, Jiangbei District, Shapingba District, Jiulongpo District, Nanan District, Beibei District, Yubei District, and Banan District are traditionally known as the central urban areas (also called the nine districts of the central city). According to the space function planning of the land, Chongqing is divided into three major functional areas: the central city metropolitan area, the urban cluster of the Three Gorges Reservoir area in northeast Chongqing, and the urban cluster of the Wuling Mountain area in southeast Chongqing. Chongqing has undulating topography and multiple geomorphic types, with many sloping fields. Specifically, mountains, hills, river valleys, and flat areas account for 76%, 22%, and 2% of the land respectively. The city boasts dense river networks, with the mainstream of the Yangtze River running through it from west to east.

The industrial enterprises involved in this study are mainly industrial enterprises registered and operating in Chongqing, referring to enterprises covered by industrial sectors such as mining, manufacturing, electricity, heat, gas and water production, and supply as classified in the Industrial Classification for National Economic Activities (GB/T 4754–2017). The data on industrial enterprises in this study are mainly obtained from the data collation of enterprise directories, including the China Business Directory and the China Manufacturing Enterprise Directory, while the data on enterprise attributes such as industry classification and registered capital are obtained by comparing the information on enterprise attributes provided by authoritative websites such as Gaode Map's POI data and Tianyancha. Taking into account the

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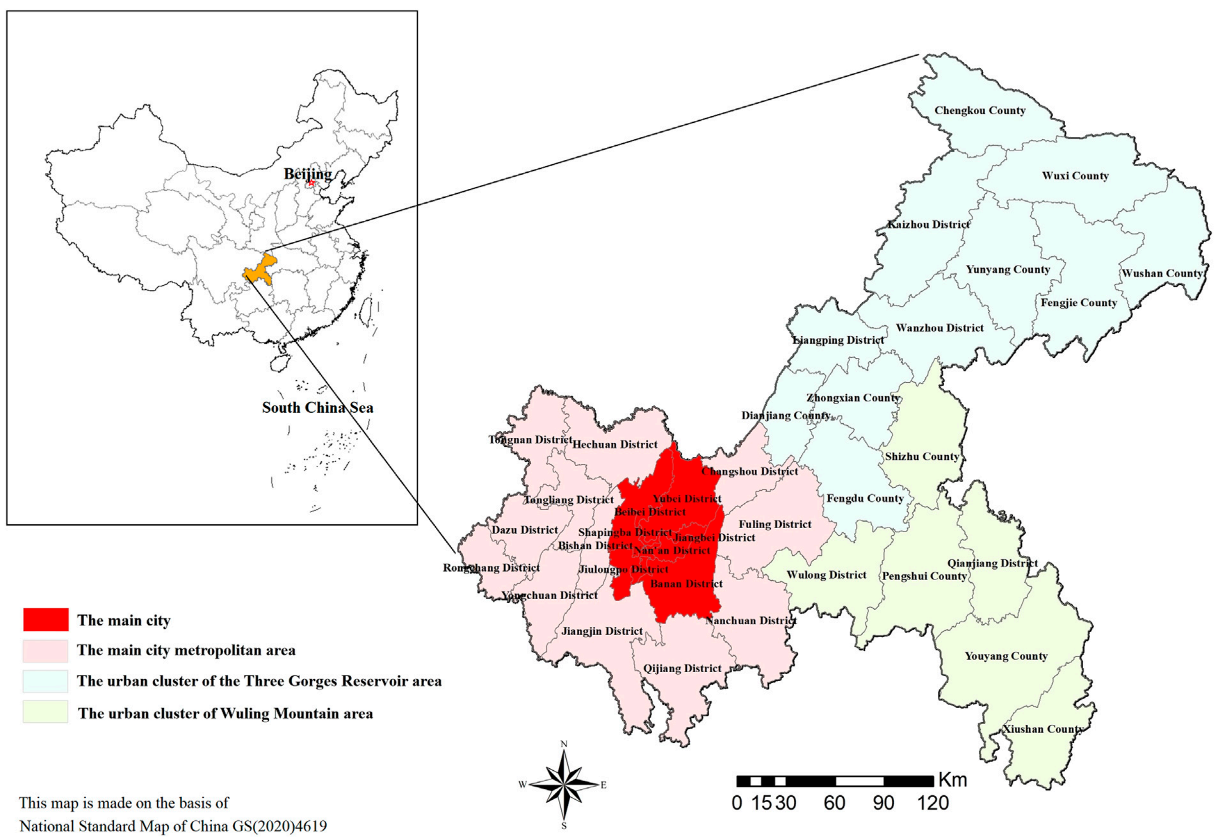

FIGURE 1
Administrative divisions and functional divisions of Chongqing.

actual situation of the study, only enterprises with a registered capital of more than one million were selected as research objects, and a total of 10,469 cases of enterprise data were obtained. Based on the enterprise directory data, this study acquired the spatial coordinate information of each industrial enterprise from Baidu API and constructed a spatial distribution database of industrial enterprises in Chongqing through the ArcGIS10.4 platform.

In this study, the GDP of the locations of industrial enterprises was used to represent their levels of economic location. Data on GDP, population density, topography, average annual precipitation, and accumulated temperature were obtained from the 2019 data sets of kilometer grids provided by the Resource and Environment Science and Data Centre of the Chinese Academy of Sciences (http://www.resdc.cn/), while data on rivers and road networks were collected from the National Geomatics database. Considering the representativeness of indicators, this study, based on the data of the kilometer grids, divided 2km×2 km grids according to the average floor area of medium and large industrial enterprises, and obtained the average values of factors such as average annual precipitation, population density, GDP, and elevation of the grids according to the geographical coordinates of industrial enterprises, with the values corresponding to the target industrial enterprises. The distance to national highways, county highways, and the city center were all calculated based on the neighborhood analysis function of the ArcGIS10.4 platform.

2.2 Methods

2.2.1 Spatial auto-correlation analysis

Spatial auto-correlation theory can be used to solve the problem of whether industrial enterprises are clustered or not, divided into global spatial auto-correlation and local spatial auto-correlation. The global spatial auto-correlation describes the overall distribution of a phenomenon and determines whether there is agglomeration of this phenomenon in the region. According to the purpose of the study, only the existence of spatial agglomeration of industrial enterprises and the overall degree of agglomeration need to be clarified, without knowing the exact location where the agglomeration occurs, so Moran's I index is chosen to measure the global spatial auto-correlation characteristics.

$$I = \frac{n}{\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}} \bullet \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}\left(Y_i - \bar{Y}\right)\left(Y_j - \bar{Y}\right)}{\sum_{i=1}^{n}\left(Y - \bar{Y}\right)^2}, \quad (1)$$

Where, I is Moran's I: Y_i and Y_j the observed sample values of i and j in every unit spatially, $\bar{Y}$ the average value of the observed value of Y; n the number of samples; W the spatial weight matrix. The value of Moran's I ranges between [-1,1]. If it is positive, it signals spatial agglomeration. If not, it refers to spatial separation. 0 stands for random distribution spatially. Different spatial weight matrixes result in different Moran's I values, and this study chose the matrix setting in ArcGIS10.4.

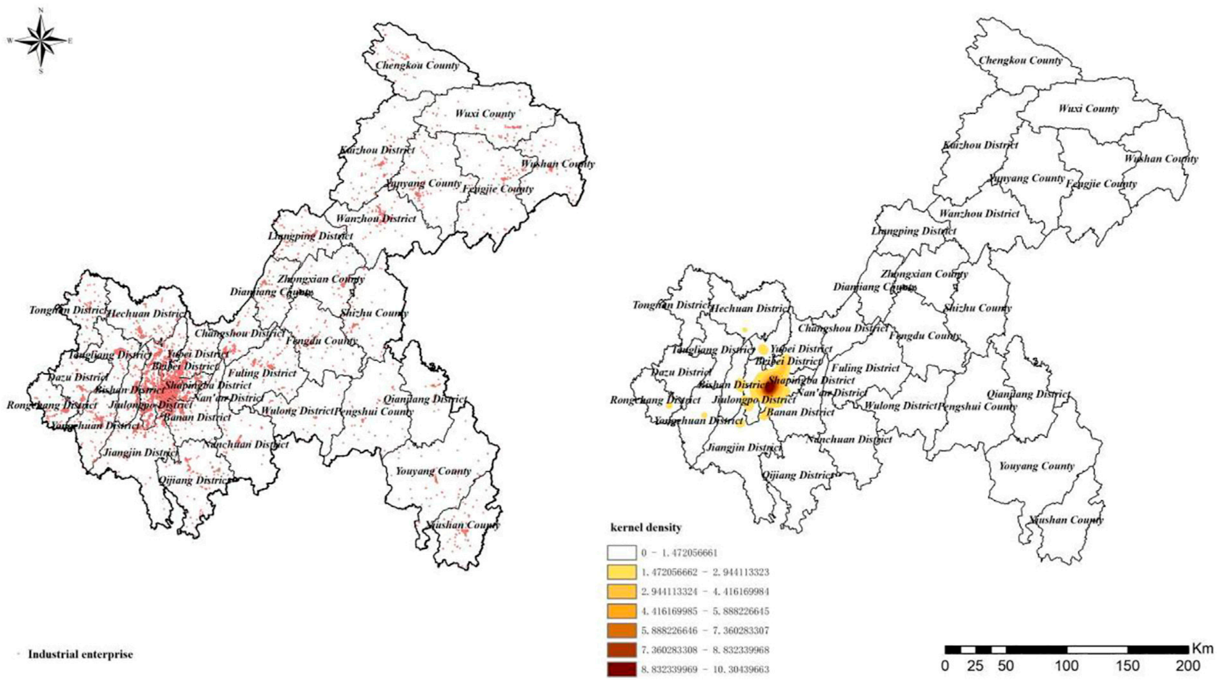

FIGURE 2
Spatial distribution and kernel density distribution of industrial enterprises.

2.2.2 Geographically weighted Regression model

When cross-sectional data is used to establish econometric models, due to its spatial complexity, auto-correlation and variability, the influence of explanatory variables over the explained variables may vary between different regions. Therefore, it is more realistic to assume that the economic behavior between regions has spatial heterogeneity and difference. Geographically weighted regression models are usually used to address this issue McMillen (2004).

$$y_i = \beta_0(u_i, v_i) + \sum_{i=1}^{k} \beta_i(u_i, v_i) x_{ik} + \varepsilon_i, \quad (2)$$

Where: x and y are independent variables and dependent variables respectively, k is the number of independent variables, j is the sample point, β_0 (u_i、 v_i) is the intercept, β_i (u_i,v_i)is the regression coefficient, ε_i is the residual term, which complies with normal distribution. The weight of each sample point is usually determined by Gaussian kernel function.

2.2.3 Baidu API

Baidu Maps provides developers with rich interfaces such as JavaScript, iframe, WebService and httpandxml, covering positioning, mapping, search, eagle-eye tracks, navigation routes, road conditions, and other functions. Developers can access Baidu's services and data to create fully functional and interactive map applications. It supports browser-based map application development for PC and mobile, and supports map development with HTML5 features. The forward/reverse geo-coding function can be used to obtain the latitude and longitude of the corresponding location, which can be used at any time by requesting the Baidu Map application using *Python*'s requests module. The development documentation of Baidu Maps can be found at http://lbsyun.baidu.com/index.php. title = webapi/guide/webservice-geocode-ing.

3 Results

3.1 The spatial distribution and economic locations of industrial enterprises

ArcGIS10.4 was used to visualize the spatial distribution of industrial enterprises in Chongqing, and the kernel density analysis method was used to draw a density distribution map of industrial enterprises in the city (Figure 2). At the municipal level, industrial enterprises in Chongqing are mainly concentrated in the nine districts of the central city, accounting for 49.67% of the total. The distribution of kernel density shows a single-kernel aggregation pattern, with the distribution declining from the high-density areas to the periphery.

At the county level, industrial enterprises are also concentrated in the counties or traditional regional central towns, such as the central urban areas of Wanzhou and Fuling Districts (Figure 3). In terms of urban functional zoning, 81.29% of industrial enterprises are distributed in the central city metropolitan area of Chongqing, with Jiulongpo, Yubei, and Shapingba Districts making up the largest proportions of 12.70%, 9.10%, and 6.89% respectively. 12.71% of industrial enterprises are located in the urban cluster of the Three Gorges Reservoir area in northeast Chongqing, with Wanzhou District, Fengjie County, and Yunyang County accounting for the largest proportions of 1.55%, 1.45%, and 1.44% respectively. 6.00% of industrial enterprises are distributed in the urban cluster of the Wuling Mountain area in southeast Chongqing.

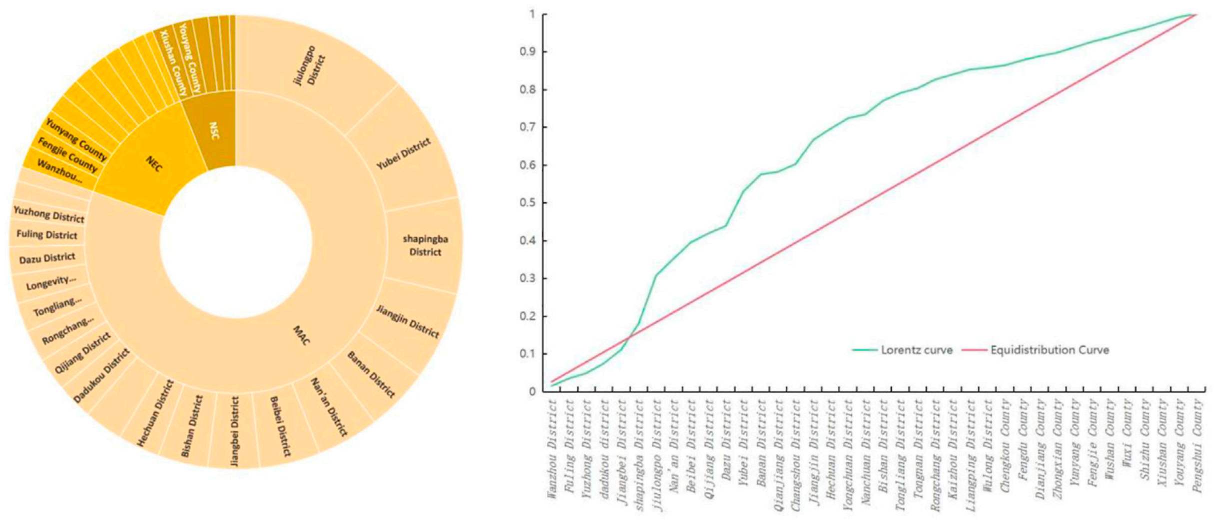

FIGURE 3
Regional distribution of industrial enterprises in Chongqing.

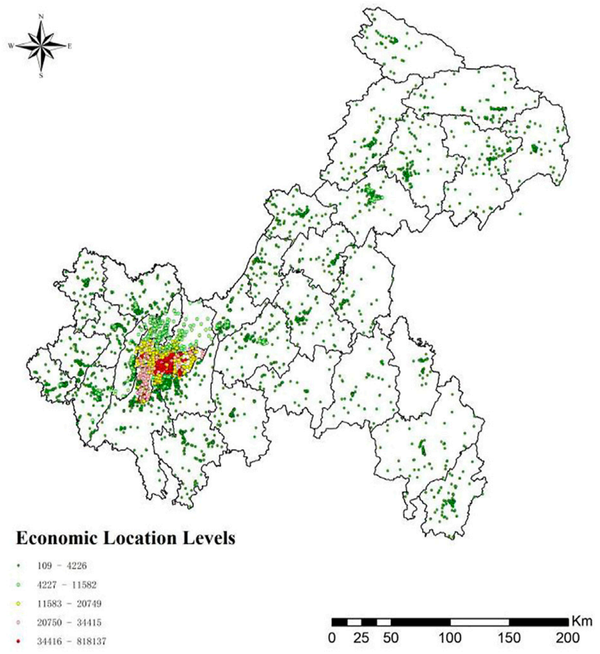

FIGURE 4
Economic location levels distribution of industrial enterprises in Chongqing.

The spatial distribution characteristics of the economic location levels of industrial enterprises in Chongqing are shown in Figure 4, showing obvious clustering characteristics in space. According to the spatial autocorrelation analysis, the Moran's I value for the economic location levels of industrial enterprises in Chongqing is .4233, the Z score is 5.956, and the *p*-value is .00, indicating that the spatial combined effect is relatively significant and has a strong positive correlation. However, there are certain differences. For example, industrial enterprises in the nine districts of the central city perform significantly better than those in other districts and counties in terms of the economic location level.

3.2 Analysis of the differences in the spatial distribution of industrial enterprises

Natural and unnatural factors such as transportation, climate, topography, and the level of economic development all have an impact on the location choice and economic location formation of industrial enterprises. Therefore, this study describes the location characteristics of industrial enterprises in Chongqing from the following aspects.

3.2.1 Transportation accessibility

Transportation accessibility, the shortest traffic route to a place, is an essential factor for the production and operation of industrial enterprises. To investigate the spatial heterogeneity of industrial enterprises' distribution in terms of transportation accessibility, this study firstly calculated the spatial distances between industrial enterprises from road networks at different levels and conducted an overlay analysis of industrial enterprises and road networks (Figure 5). The results showed that about 93.50%, 60,34%, 96.67%, and 97.57% of industrial enterprises in Chongqing have distributed within a 10 km range away from the motorway networks, national highways, provincial highways, and county highways respectively, among which about 22.33%, 16.29%, 54.15%, and 43.39% of industrial enterprises are located in the 1 km buffer zone of the motorway networks, national highways, provincial highways, and county highways respectively (Figure 6). The accessibility is closely related to the spatial distribution of industrial enterprises. As better transportation accessibility facilitates the smooth circulation of production factors and goods such as raw materials, energy resources, and labor force, more industrial enterprises are located close to road networks, with higher levels of clustering and lower costs of industrial production.

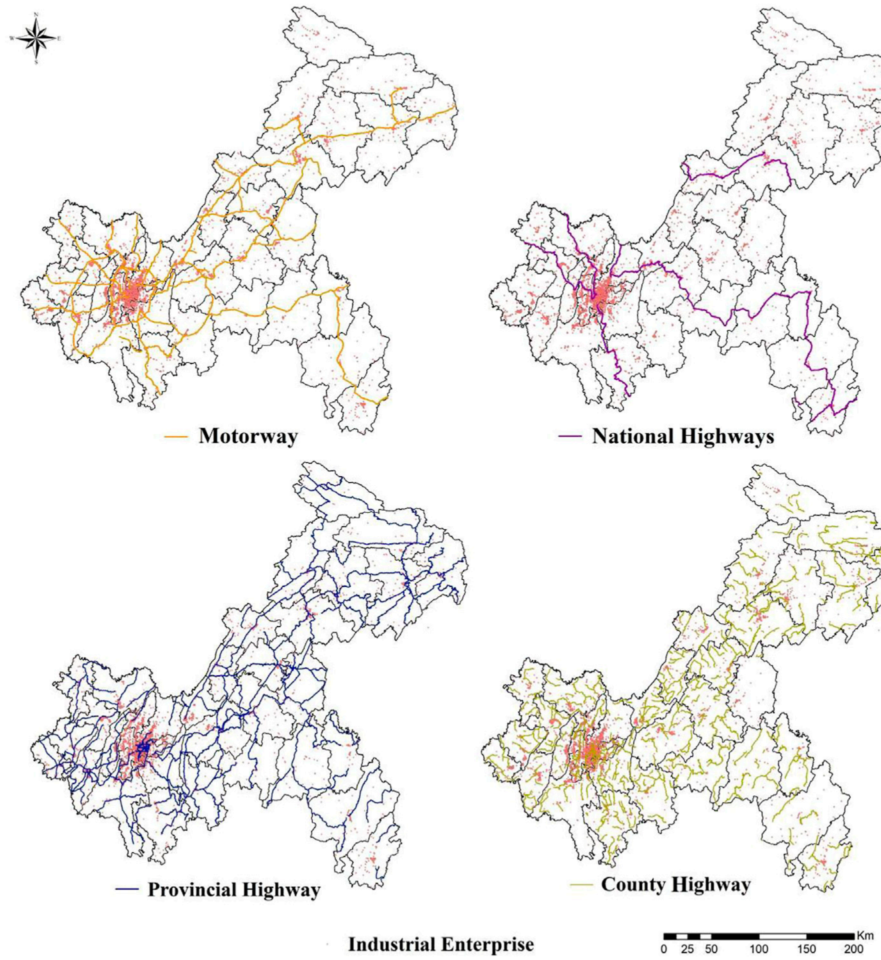

FIGURE 5
Transportation Accessibility characteristics of industrial enterprises in Chongqing.

3.2.2 Distance to river systems

Chongqing has a dense network of rivers, with the upper reaches of the Yangtze River and its major tributaries such as the Jialing River, the WuJiang River, and the QiJiang River flowing through. Industrial enterprises in the city are mostly located along rivers due to production and business needs, such as energy consumption, water transportation, water drawing, and pollution discharge. This study calculated the spatial distances between industrial enterprises and the Yangtze River and its important tributaries and conducted an overlay analysis of the industrial enterprises and the river system (Figures 7, 8). The results show that about 73.57%, 56.72%, and 19.42% of industrial enterprises in Chongqing are distributed within the 10km, 5km, and 1 km buffer zones of the Yangtze River and its major tributaries, respectively, and these enterprises show prominent characteristic of being located along rivers.

3.2.3 Distance to central towns

Traditional central towns in various regions are, on the one hand, important places for the procurement and trading of production and living goods for the production and operation of industrial enterprises, and market for leisure and consumption on the other. The distance to central towns influences the economic location selection of industrial enterprises to a certain extent. Therefore, this study measured the shortest spatial distances between industrial enterprises and traditional regions and conducted a spatial overlay analysis. The results showed that about 64.83%, 33.36%, and 4.63% of the industrial enterprises are located within the spatial buffer zones that are 10 km, 5 km, and 1 km away from the central towns, respectively (Figures 7, 8).

3.2.4 Topographical factors

Chongqing has strongly undulating topography and diverse geomorphic features, with an average altitude of 734 m. While the west part of the city is low-lying, the east part has a higher altitude. Topographic conditions play a significant play in the location selection of industrial enterprises. This study conducted statistics on the altitudes of industrial enterprises and found that 93.48% of the enterprises are located below 800 m above sea level, and 49.82% of industrial enterprises have an altitude ranging from 500 to 600 m above sea level (Figures 7, 8).

3.2.5 Population density

The labor force is a crucial input factor for industrial production, and population density is a strong attraction for

FIGURE 6
Distribution of the number of industrial enterprises in different buffer zones (1). (in which, **(A–D)** denotes radius buffer zones for motorway, national highways, provincial highways, and county highways respectively).

industrial enterprises that are about to choose a location. According to the kilometer grid map of population density and the spatial overlay analysis of industrial enterprises in 2020, about 52.36% of industrial enterprises are located in areas with a population density of 50-150 people/km^2, about 21.06% in areas with a population density of 3051-7050 people/km^2, and 11.47% in areas with a relatively high population density of 5051-6050 people/km^2 (Figures 7, 8).

3.3 Analysis of the formation of the economic locations

To further explore the formation and constraints of the economic locations of industrial enterprises in Chongqing, this study took GDP, which reflects the economic locations of industrial enterprises in Chongqing, as the dependent variable, and selected, based on the bibliographic index, factors related to the location selection of industrial enterprises, such as transportation accessibility, distance to river systems, distance to central towns, population density, topography, precipitation, air temperature, and accumulated temperature, as the dependent variables, and selected, through correlation test, tolerance test, and VIF test, six indicators including the DMW,DNH,DCH, DCC, DR, and POP, to construct a spatial regression model (Table 1). Meanwhile, the GWR model and ordinary least squares (OLS) model were compared to avoid the possible contingency of a single model.

3.3.1 The parameter estimation of the OLS model

The parameter estimation of the OLS model (Table 2) shows that the VIF values are all less than 7.5, indicating low multicollinearity of the explanatory variables. According to the T statistic and *p*-value, DMW, DNH, DCH, DCC, DR, and POP exceed the 1% significance level, and all have significant impacts on the economic location distribution of industrial enterprises. In terms of the coefficient of influence, except for DMW, all other factors show the same trend as the economic location distribution of industrial enterprises. In other words, the shorter the distance to national highways, county highways, river systems, and central towns and the higher the population density is, the higher the GDP of the economic location is, while DMW shows a reverse trend, indicating that a longer distance from highways means better economic location conditions of industrial enterprises, which is consistent with the distribution trend of highways far from towns and cities.

3.3.2 The parameter estimation of the GWR model

The OLS model considers space to be homogeneous and only considers the global characteristics of the regression coefficients, ignoring the spatial differences at each local regional level. Therefore, this study constructed a GWR model based on GWR4.0 to analyze the spatial differences in the formation of the economic locations of industrial enterprises in Chongqing from the perspective of spatial heterogeneity.

The results of the model calculations (Table 3) show that the AICC value of the GWR model is much smaller than that of a general OLS

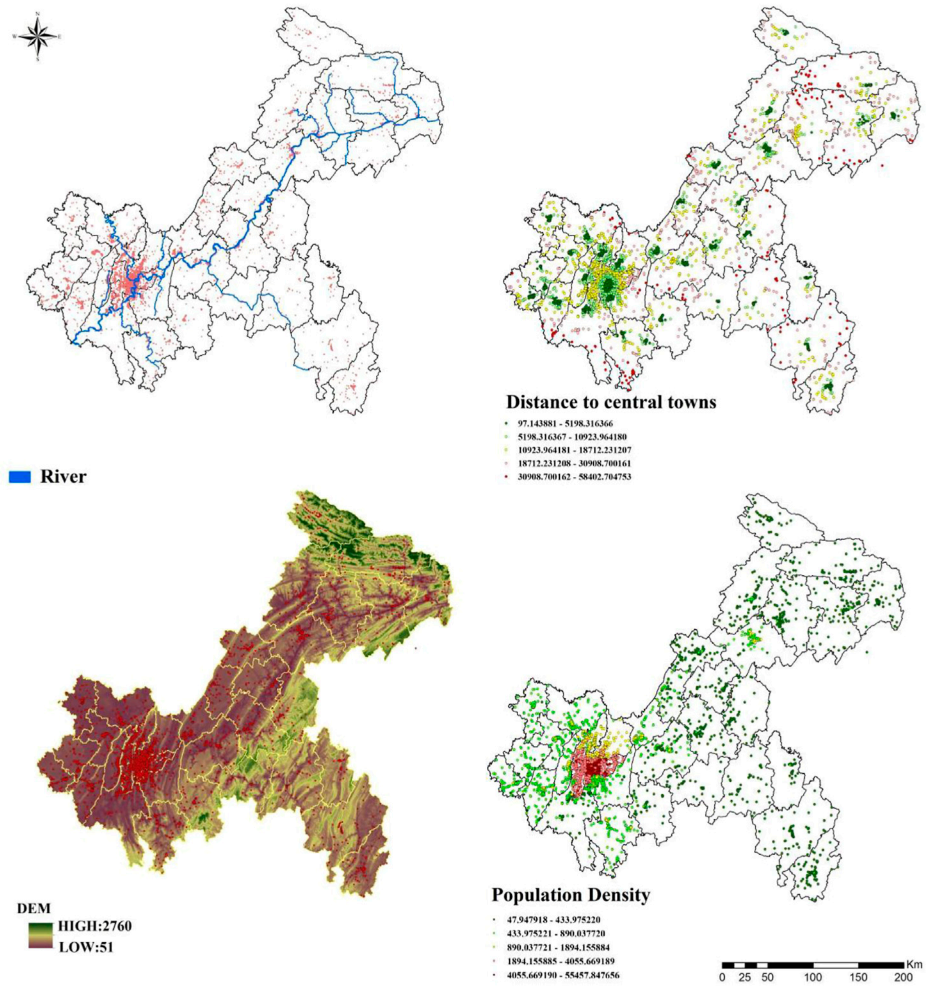

FIGURE 7
Spatial characteristics of the distribution of industrial enterprises in Chongqing.

regression, and the GWR model regression has higher adjusted goodness of fit than the general OLS model. In summary, the importance and necessity of using the GWR model estimation in this study can be verified.

Meanwhile, considering that the impact of each influencing factor on the economic location levels of industrial enterprises varies with spatial location, this study further visualized the regression results of the GWR model coefficients to highlight the hysteresis effect and spillover effect of its regression coefficients in geographic space.

As shown in Figure 9, DMW is negatively correlated with the economic location levels of industrial enterprises (i.e. a shorter distance to the highway network corresponds to a lower economic location level). The high and low values of the regression coefficients are mainly concentrated in the nine districts of the central city, among which Yuzhong and Nanan Districts, both located in the center of Chongqing and are the economic and financial centers of the city, are typical low-value districts. With GDP per unit area of land much higher than that of other districts and counties, these two districts have a long history of urban construction and road construction. They are far away from motorway networks, so they present low regression coefficients. Jiangbei and Yubei Districts, as new economic zones drastically developed in Chongqing in recent years, have a higher demand for the accessibility and efficiency of logistics, so they have the densest motorway networks in all districts and counties. Therefore, their regression coefficients are mainly positive values (i.e. a shorter distance to the highway network corresponds to a higher economic location level). Transportation accessibility indicators such as DNH, DR, and DCH are mainly positively correlated with the spatial distribution of industrial enterprises. Similar differences in regression coefficients caused by urban construction, road construction, and industrial development are also reflected in DNH and DR. For example, districts and counties such as Shapingba, Jiulongpo, and Nanan have a long history of development and prospered thanks to major transportation routes such as national highways, provincial highways, and the Yangtze River water system in the early days. Therefore, the spatial distribution of industrial enterprises in these regions is closely related to these transportation routes, and the economic location level presents the distribution characteristics of "a shorter distance to the main transportation routes corresponding to a higher regression coefficient". In addition, regarding urban functional zoning, the regression coefficients of the central city metropolitan area are higher than those of other functional areas.

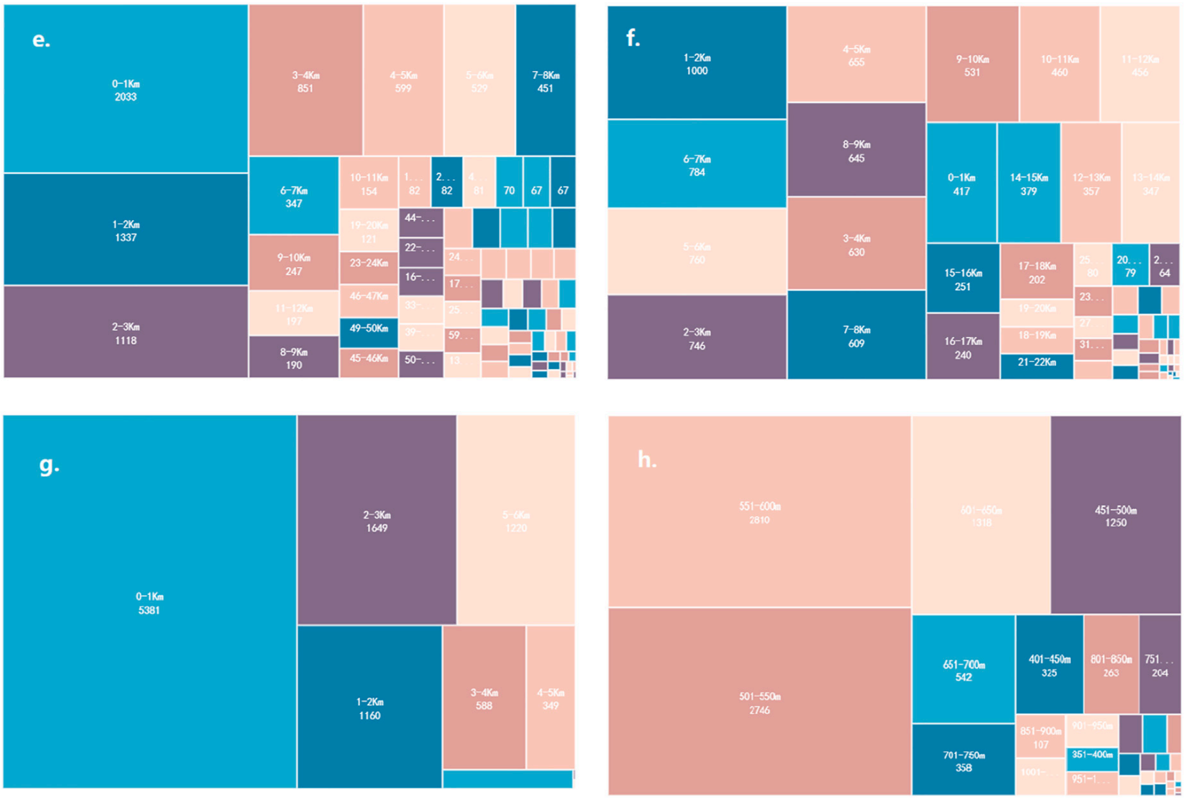

FIGURE 8
Distribution of the number of industrial enterprises in different buffer zones (2). (in which, **(E–H)** denotes radius buffer zones for river, central towns, population density, and DEM respectively).

TABLE 1 Model parameters description.

Parameters	Unit	Parameters definition	Source
DMW	Km	Distance to motorway networks	Calculated in ArcGIS10.4
DNH	Km	Distance to national highways	Calculated in ArcGIS10.4
DCH	Km	Distance to county highways	Calculated in ArcGIS10.4
DCC	Km	Distance to central towns	Calculated in ArcGIS10.4
DR	Km	Distance to rivers	Calculated in ArcGIS10.4
POP	people/km^2	Population density	Calculated in ArcGIS10.4

In terms of the impact of DCH, Jiangbei District, Yubei District, and some emerging regions, such as Fengdu District and Qijiang District, show relatively low densities of national highways and provincial highways due to their relatively late urban development, but their transportation lines densities are higher, specifically reflected in more well-distributed and dense county highway networks, so the regression coefficients of DCH of these districts and counties show greater differences than those of DR.

The DCC indicator measures the extent to which the economic location of an industrial enterprise is away from central towns, and its regression coefficient is mainly positive. From the perspective of urban functional zoning, the economic locations of industrial enterprises in the urban cluster of the Three Gorges Reservoir area in northeast Chongqing and the urban cluster of the Wuling Mountain area in southeast Chongqing have a tendency of being close to central towns, where shorter distances to central towns of the regions correspond to better economic location conditions of industrial enterprises. Regions in the central city metropolitan area, by contrast, present drastic spatial differences. The distribution of industrial enterprises in Yubei, Nanan, and Yuzhong Districts is entirely different from that in Jiulongpo and Shapingba Districts. The former shows a significant positive correlation, while the latter shows a significant negative correlation, which is closely related to the industrial categories of the industries enterprise in those regions. Environment-friendly industries, such as precision instruments and high-tech industries, tend to cluster in central urban areas such as Nanan District and Yubei

TABLE 2 Model parameters of the OLS model.

Parameters	Coefficient	T	P	Std	VIF
DMW	−.068	−9.325	000 ***	007	1.471
DNH	046	15.200	000 ***	003	1.510
DCH	146	3.185	000 ***	019	1.151
DCC	107	15.173	000 ***	007	1.153
DR	030	.000	000 ***	004	1.241
POP	9.248	310.557	000 ***	030	1.318
C	−6129.929	−47.351	000 ***	129.456	NA
R^2			9184		
Adjusted R^2			9183		
AICC			208586		

C stands for the intercept, "*" stands for passing 10% of the significant level test, "**" stands for the passing 5% of significant level test, and "***" stands for passing 1% of the significant level test.

TABLE 3 Model parameters of the GWR model.

Metrics	Value
Bandwidth	451.817
AICC	179029
R^2	9954
Adjusted R^2	9952

District. In contrast, Jiulongpo District houses a lot of high-energy consuming and polluting medium and large industrial enterprises such as Chongqing Power Plant and Jiulongpo Power Plant that both big consumers of coal. As these enterprises are generally far away from the central towns, the regression coefficients for the nine districts of the central city greatly vary. In general, POP positively impacts the economic location levels of industrial enterprises in a significant manner, except in very few districts. In particular, the impacts of POP on the economic location levels of industrial enterprises are the most significant in the nine districts of the central city, while the traditional central towns in various regions, such as Wanzhou, Yongchuan, and Fuling Districts all represent relatively high regression coefficient, indicating that places that are more densely populated can better economic location conditions of industrial enterprises and the population factor drastically drives the selection and formation of enterprise locations.

4 Discussion

The spatial heterogeneity of industrial enterprises and the formation of their economic locations are jointly caused by natural, social, economic, and policy factors that are acting together and accumulating in cycles, and the formation of micro enterprises' economic locations is also a specific manifestation of regional economic and industrial development (Chisholm, 1971; Golley, 2002; Uwe Deichmann et al., 2008; Zhang et al., 2021). Existing studies on the distribution and economic locations of industrial enterprises are mostly focused on micro individuals, such as the location formation of single industrial enterprises, such as Chemical industry and steel industry (Abrudan et al., 2016; Powe and Willis, 1998; Wu and Yang, 2018), or on regions from a macro and holistic perspective (Rayp, 2015; Wang Q. et al., 2020). The research data are mainly based on micro-surveys and statistical yearbooks, and the research conclusions generally face the problem of poor spatial heterogeneity. This study, integrating the two dimensions, started from the micro individuals of industrial enterprises in Chongqing and discussed the spatial distribution of these enterprises and the formation of their economic locations based on text data mining, POI, and spatial information technologies, revealing the spatial differences in the formation of the economic locations of industrial enterprises, and to a certain extent bridging the gap between the "micro-individual" and "macro-whole" studies in research on industrial location.

In the industrial development layout of most cities, industrial enterprises tend to expand along primary transportation routes to enjoy more favorable economic locations. For example, industries in Houston, United State, develop along the highway axis of the Gulf of Mexico; heavy chemical industries in the Ruhr industrial region, Germany, concentrate along the Rhine River; heavy industries in the old industrial bases in Northeast China are distributed and expand along railways (Bremer and Sander, 2004; Can-Fei et al., 2008). This study used the GWR model to study the formation of the economic locations of industrial enterprises in Chongqing through transportation accessibility indicators such as DNH, DCH, and DR. The results showed that DNH, DCH, and DR have significant positive impacts on the formation of the economic locations of industrial enterprises, and DMW has a certain negative impact. There is strong spatial heterogeneity in the impacts according to the type of industry and the actual situation of road traffic in various regions. DNH and DR show significant spatial differences. Specifically, as the urban construction and industrial enterprises in Chongqing were mostly distributed along the main tributaries of the Yangtze River and main transportation routes such as national and provincial highways in the early years, the economic locations

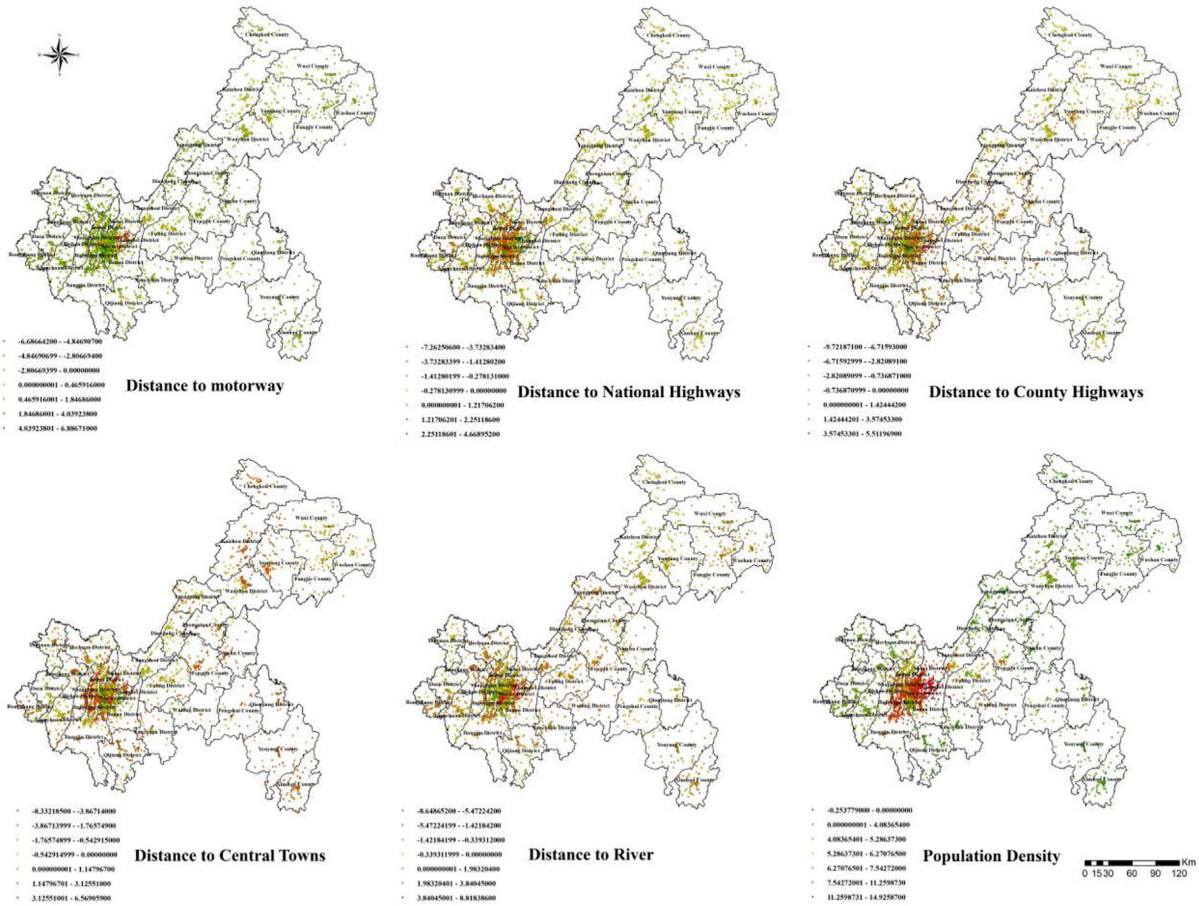

FIGURE 9
Spatial distribution of the regression coefficients of various influencing factors Estimated by the GWR model.

of industrial enterprises in the traditional agglomeration areas of such enterprises such as Jiulongpo and Nanan Districts show a strong positive spatial correlation with DNH, DCH, and DR, while new economic development zones or hi-tech development zones have new manufacturing industries and export-oriented economies and higher requirements for logistics accessibility and efficiency for industrial development (A et al., 2014; Chen et al., 2022), such as Yubei and Jiangbei Districts, which also attach great importance to transportation location conditions, as shown by the extremely high regression coefficients of enterprises in these regions in terms of DMW, coupled with denser county highway networks.

The environment is a pivotal factor in the formation of economic locations of industrial enterprises. Tian constructed the regional-industrial interaction model and used a panel data model to demonstrate that the inhibiting effects of environmental factors on polluting industries have become increasingly obvious in recent years (Tian et al., 2018). Liu further studied the effect of environmental regulation on the spatial spillover of industrial pollution and found that environmental regulation has a significant inhibiting effect on the spillover of industrial pollution (Liu et al., 2021). This is reflected in whether the economic locations of industrial enterprises in Chongqing are close or far from central towns. For example, in traditional old industrial areas such as Jiulongpo and Shapingba Districts, polluting enterprises including Chongqing Power Plant and Jiulongpo Power Plant are located far from central towns (i.e. a longer distance to central towns corresponds to better economic location conditions). This is contrary to the expected effect of the OLS global regression but also more in line with the reality of industrial development. Taking Jiulongpo District as an example, it is currently vigorously carrying out industrial structure upgrading, eliminating and relocating a number of high energy-consuming enterprises. With the further implementation of China's Yangtze River protection strategy, similar high polluting and energy-intensive enterprises will move further away from the central towns and the main tributaries of the Yangtze River (Hou et al., 2021). In addition, the population factor has been widely discussed in studies on industrial economic location. Generally speaking, higher population densities mean more abundant labor resources and vast product consumption markets and lead to better economic location conditions for enterprises. Through the relationship between population mobility and economic growth in Chongqing, Li showed that the population factor has a significant inhibiting effect on regional economic growth, and the driving effect of industrial investment on the economy is more obvious in densely populated areas than in sparsely populated areas (Xiao-Yang et al., 2018). Yang also showed, through the study on population density and enterprise productivity, that population density, when it exceeds a certain threshold, has a significant promoting effect on enterprise productivity (Yang et al., 2018). In the conclusion of this study, the high regression coefficients of high population densities in the nine districts of the central city on enterprises' economic locations are consistent with the research conclusions to a certain extent.

5 Conclusion

Based on spatial information technologies such as POI and API, as well as GWR, this study, taking Chongqing, a municipality directly under the central government in Western China, as an example, investigated the characteristics of spatial distribution and economic locations of industrial enterprises in the city, as well as how these characteristics took shape. The results showed that factors such as DNH, DCH, DR, DCC, and POP have significant positive impacts on the formation of economic locations of industrial enterprises, while DMW exerts a certain negative influence. There is strong spatial heterogeneity in the impacts according to the type of industry and the actual situation regional industrial development in various regions. In addition, factors related to transportation accessibility, environment, and labor force play a moderating role in the formation of economic locations of industrial enterprises. In a nutshell, it provides some theoretical and practical basis for formulating reasonable industrial spatial planning, guiding industrial development, and alleviating urban problems to explore the spatial distribution and economic location characteristics of industrial enterprises in Chongqing at the spatial level.

This study has the following main limitations. Firstly, in terms of the selection of industrial enterprises, only ones with a registered capital of more than one million were selected, which may not be representative enough. Secondly, in terms of the factors related to the formation of economic locations, the indicators, restricted by the availability of micro-data, are not comprehensive enough, and there is a lack of sufficient verification of the data accuracy. In the follow-up work, we will further strengthen the discussion and research on the above issues.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

ZT conceived and designed the experiments; ZT, MF performed the experiments; ZT, YW analyzed the data; ZT contributed materials/analysis tools; ZT, MF, YZ, and YW wrote the paper, ZT reviewed drafts of the paper.

Funding

We gratefully acknowledge the Supported by National Social Science Fund of China (20CJL022).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 02 February 2023
DOI 10.3389/fenvs.2023.1126565

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OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Environmental Economics and Management, a section of the journal Frontiers in Environmental Science

RECEIVED 18 December 2022
ACCEPTED 18 January 2023
PUBLISHED 02 February 2023

CITATION
Xiong L, Long H, Zhang X, Yu C and Wen Z (2023), Can environmental information disclosure reduce air pollution? Evidence from China.
Front. Environ. Sci. 11:1126565.
doi: 10.3389/fenvs.2023.1126565

Can environmental information disclosure reduce air pollution? Evidence from China

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Previous studies have focused on the reduction effect of regulation-based instruments and economic-based instruments on air pollution, ignoring the importance of environmental information disclosure. Based on the Ambient Air Quality Standards (AAQS), a quasi-natural policy implemented in 2012, this paper assesses the effect of environmental information disclosure on air pollution through a dynamic spatial difference-in-difference (DID) model using panel data of 269 cities from 2006 to 2017 in China. We find that the implementation of the AAQS results in a 3% reduction of local $PM_{2.5}$ concentration and a 3.3% reduction of $PM_{2.5}$ concentration in the surrounding cities. Further analysis suggests that environmental information disclosure reduces air pollution through enhancing public environmental concerns, green innovation, and industrial upgrading. We also explore the moderating effect of government environmental regulation and heterogeneity analysis in different regions. Our findings suggest that government should further develop the scope and quality of environmental quality information disclosure. Moreover, the local government should provide more support for the green transformation of enterprises and provide necessary support during the transition period. In addition, long-term sustainable environmental protection policies must be able to mobilize regional initiatives for green development.

KEYWORDS

air pollution, environmental information disclosure, ambient air quality standards, dynamic spatial difference-in-difference model, spillover effects

1 Introduction

In recent years, China's rapid economic growth has also brought about serious environmental pollution problems (Yu et al., 2021; Bao and Liu, 2022; Duan et al., 2022; Wu et al., 2022). Especially since 2011, air pollution, represented by haze, has received increasing attention. The most important task to deal with haze pollution and improve air quality is to control $PM_{2.5}$ concentration (Wang et al., 2021b; Hopke and Hill, 2021; Jin et al., 2022; Lin et al., 2022; Renard et al., 2022; Che et al., 2023). As an air pollutant with small particles, $PM_{2.5}$ can enter the respiratory system from the lungs, thus leading to an increased prevalence of respiratory and neurological diseases (Varotsos, 2013; Bu et al., 2021; Yang et al., 2021; Liu et al., 2022a; Gan et al., 2022; Yuan et al., 2022). In addition, increased $PM_{2.5}$ concentration significantly limit all types of outdoor activities, resulting in economic losses (Wang et al., 2020). Therefore, how to control $PM_{2.5}$-based air pollution has become an important academic topic.

Governmental environmental regulation is considered to be an important measure to control air pollution (Chen et al., 2022). In general, government policy instruments for implementing environmental pollution control can be divided into three main categories (Hanley et al., 2016), which are regulation-based instruments, economic-based instruments, and information-based instruments. The evolution of these three policy instruments represents the developmental stages of government environmental regulation (Ding et al., 2022). In the first stage, environmental pollution was restricted mainly through regulation-based instruments. The second stage further promotes the green transformation of firms by raising the costs of high polluting enterprises through market mechanisms. The third stage requires cities or firms to disclose more detailed environmental information to be monitored by the government and the public. In recent years, China's rapid economic growth has been underpinned by the increasingly serious problem of air pollution (Gangwar et al., 2019; Li and Lu, 2020). The excessive focus on economic development has led local governments to pay less attention to pollution control, resulting in a large number of firms circumventing environmental regulation and emitting various air pollutants illegally (Zhang et al., 2020; Zhang et al., 2022b). Thus, relying only on regulation-based instruments or economic-based instruments is still unable to effectively control air pollution in China. Due to the lack of information disclosure on air pollution in China, the public is unable to effectively assess the air quality in their location, and the government does not have sufficient incentive to strengthen environmental regulation (Ouyang et al., 2019; Zhang et al., 2022a). This is one of the reasons for the limited effect of regulation-based instruments and economic-based instruments on air pollution reduction. Therefore, China implemented the Ambient Air Quality Standards (AAQS) in 2012 to publish real-time $PM_{2.5}$ concentration in each city, expecting to enhance public awareness of environmental protection and local government regulation to improve air pollution.

Most of the literature focused the reduction effect of regulation-based instruments on air pollution. For example, based on cross-country panel data for 30 OECD countries from 1998 to 2015, the study of Ouyang et al. (2019) shows that the effect of environmental regulation on PM2.5 emissions is non-linear. Using panel data for 248 cities from 2003 to 2016, the study of Wang et al. (2021c) shows that an enhancement of regulation-based instruments significantly reduces air pollution. Some of the literature has also assessed the impact of measures such as the collection of emission fees on pollution control from the perspective of economic-based instruments. The study of Cui et al. (2021) holds that carbon emission trading implementation can significantly reduce your pollution emissions at the firm level. However, there is still a paucity of literature that analyzes the impact of environmental information disclosure on reducing air pollution from the perspective of environmental information disclosure. Most studies on environmental information disclosure have focused on the firm level, mainly discussing which factors enhance corporate environmental information disclosure or how corporate environmental information disclosure affects their business behavior and financial status (Liu and Anbumozhi, 2009; Zhang et al., 2010; Hassan and Ibrahim, 2012). The direct effect of environmental information disclosure on environmental pollution, which is the original purpose of environmental information disclosure, has not been emphasized. Some studies have used the Pollution Information Transparency Index (PITI) for annual evaluation of 113 Chinese cities as a quasi-natural experiment to assess its impact on environmental pollution management (Zhong et al., 2021; Zhang et al., 2022a). However, such NGO evaluation indicators often suffer from subjectivity, timeliness, and comprehensiveness (Brulle et al., 2007). Moreover, 110 of the 113 cities selected for the PITI evaluation are national environmental protection priority cities, and bias in the selection of evaluation targets may lead to biased results on effectiveness of pollution control. In addition, Liu et al. (2021a) used National Ambient Air Quality Monitoring Network (NAAQMN) as a quasi-natural experiment to evaluate its impact on reducing air pollution. The results showed that implementation of NAAQMN resulted in a reduction of $PM_{2.5}$ concentration by 1.325 mg/m^3. However, this study only focuses on the emission reduction effect of $PM_{2.5}$ monitoring station establishment and ignores the impact of environmental information disclosure from the monitoring stations. The information disclosure of $PM_{2.5}$ concentration data at monitoring stations can directly affect the public and government concerns and the effectiveness of air pollution control. Therefore, it is necessary to explore in depth the effect of environmental information disclosure, an important initiative, in reducing air pollution.

In this paper, the implementation of AAQS is used as a quasi-natural experiment to assess the impact of environmental information disclosure on reducing air pollution. First, this paper collects balanced panel data of 269 prefecture-level cities from 2006 to 2017 to assess the impact of environmental information disclosure on air pollution using a dynamic spatial DID model. Second, this paper further explores the mechanism of environmental information disclosure affecting air pollution and the moderating effect of government environmental governance. Finally, this paper also conducts some tests to ensure the robustness of the analytical results, including a placebo test, a re-estimation based on PSM-DID and a re-estimation excluding contemporaneous policy interference.

The contributions of this paper can be summarized as follows. First, most studies focus on the impact of environmental regulation on air pollution, but the impact of environmental information disclosure is ignored. With the new Ambient Air Quality Standards as a quasi-natural experiment, this paper the relationship between environmental information disclosure and air pollution. Meanwhile, with the spatial DID model, this paper further investigates the spatial spillover effect which has been ignored in current research. Our findings show that the implementation of AAQS leads to a 3% reduction in $PM_{2.5}$ concentration not only in the local area, but also in the surrounding area by 3.3%. Therefore, environmental information disclosure should be continuously promoted to improve air quality. Second, this paper discusses in depth the mechanisms by which environmental information disclosure affects air pollution and explores the moderating effect of government environmental regulation. Our findings suggest that environmental information disclosure reduces air pollution by enhancing public environmental concerns, green innovation, and industrial upgrading. In addition, this paper holds that increased government environmental regulation amplifies the air pollution reduction effect of environmental information disclosure. The mechanism analysis is extremely vital since it can be used for government policy making. Finally, this paper explores the differences in the effects of environmental information disclosure across regions. Previous studies related to environmental information disclosure and pollution control have less often analyzed heterogeneity from the perspective of heating and non-heating areas. Our findings suppose that the reduction effect of environmental information disclosure on air pollution is strongest in the eastern region. In addition, the reduction effect of environmental information disclosure on air pollution is much higher in non-heating areas than in heating areas.

The reminder of this study is organized as follows: Section 2 provides the literature review and research hypothesis, Section 3 provides the methods and data, Section 4 provides the results, and Section 5 provides the conclusions and recommendations.

2 Literature review and research hypothesis

2.1 Literature review on air pollution

Air pollution is defined as a phenomenon that occurs when certain substances invade the air in concentrations that are harmful to humans or to the ecosystem on which humans depend (Brauer et al., 2021; Wang et al., 2022c). In recent years, the frequent occurrence of highly hazardous air pollution events has brought about a high level of social concern. To shift the public from concern to better participation in monitoring air quality, a series of measurement standards have been introduced to allow the public to perceive the severity of air pollution at the data level (Lin et al., 2021). Specifically, the concentrations of sulfur dioxide, nitrogen dioxide, carbon monoxide, ozone, $PM_{2.5}$, and PM_{10} are commonly chosen to measure air pollution levels (Akbarzadeh et al., 2018). Among these sources, $PM_{2.5}$ is an important class of pollutants. Due to its small size and ability to be suspended in the air, $PM_{2.5}$ has the property of carrying pathogens (Bu et al., 2021). When $PM_{2.5}$ enters the human airways, it not only causes airway obstruction and a series of inflammatory diseases but may even cause cancer through air-blood exchange, which is very destructive to the human body (Yu et al., 2022). Therefore, when people focus on air pollution indicators, they always give priority to $PM_{2.5}$ concentration.

$PM_{2.5}$ concentration is influenced by several factors, which can be mainly classified as economic and weather factors (Wu et al., 2020). On the one hand, at the economic level, economic development, population, public transportation, and industrial structure all have an impact on $PM_{2.5}$ concentration. Ji et al. (2018) used panel data from 2001 to 2010 for 79 developing countries to quantify the socioeconomic drivers of $PM_{2.5}$ concentration. They found that the effect of urbanization level on $PM_{2.5}$ concentration differed between low- and high-income zones, showing an inverted U-shaped relationship. Li et al. (2020) studied the relationship between urban spatial structure, especially population distribution, and $PM_{2.5}$ concentration using a two-way stationary panel regression model based on panel data from 2001 to 2016 for 286 cities in China. Hao et al. (2022) constructed a high-precision estimation model for $PM_{2.5}$ concentration based on the method of gradient boosted regression tree. They verified the importance of major factors such as traffic conditions, meteorological conditions, and urban spatial layout in $PM_{2.5}$ concentration estimation and confirmed that public transportation activities contribute significantly to the increase of $PM_{2.5}$. Xue et al. (2021) reconstructed a high spatial resolution $PM_{2.5}$ datasets from 2000 to 2018 in Beijing-Tianjin-Hebei region and used vector autoregressive model to investigate the response of $PM_{2.5}$ to industrial structure. They found that the government needs to promote the optimization of industrial structure through low-carbon technology development or clean energy research to more significantly reduce $PM_{2.5}$ concentration.

On the other hand, temperature, humidity, precipitation, and sunshine duration are all important factors affecting $PM_{2.5}$ concentration. Liu et al. (2022b) evaluated the specific contribution of weather patterns to $PM_{2.5}$ concentration based on spatial effects and health risks. They found that pollutants tend to accumulate in small spaces when the temperature and humidity are high in the region. Moreover, higher relative humidity enhances hygroscopic growth and multiphase reactions of aerosols and inhibits the diffusivity of air pollutants. Therefore, temperature and humidity tend to be positively correlated with $PM_{2.5}$ concentration. Zhang et al. (2021) analyzed the effects of two winter precipitation events on $PM_{2.5}$ in Beijing in 2015 and 2016, respectively. Based on the simulation results, they found that precipitation had a significant effect on $PM_{2.5}$ removal when atmospheric dispersion conditions were favorable. Yang et al. (2022a) took sunlight into account when studying the effect of $PM_{2.5}$ exposure on vitamin D status of pregnant women. They found that $PM_{2.5}$ exposure had a significant effect on vitamin D deficiency under weather conditions with short daylight hours. After further analysis, they concluded that the ability of $PM_{2.5}$ to absorb solar radiation causes a negative correlation between sunlight duration and $PM_{2.5}$ concentration. In addition, factors such as the level of environmental regulation by the government can also influence $PM_{2.5}$ concentration (Yu et al., 2021).

2.2 Policy background of ambient air quality standards in China

Similar to other countries, the environmental policies adopted by the Chinese government began with legal constraints based on administrative orders (Yao et al., 2022). Early legal regulations often had a significant environmental improvement effect. However, as productivity developed and production demand increased, many companies began to bypass environmental regulations for production violations, which led to a sharp decline in environmental quality (Gangwar et al., 2019; Li and Lu, 2021). To continuously improve the environment, promote government regulation, and strengthen public oversight, China has begun to focus on the role of environmental information disclosure in pollution control and to meet public demand for environmental information disclosure (Tian et al., 2016). Ambient Air Quality Standard promulgated in 2012 is a policy product of this background. This standard requires that air quality data must be released to the public in a uniform, real-time, and comprehensive manner (Bai et al., 2021). In addition, the government will announce in four batches the monitoring stations set up in the corresponding cities nationwide for the establishment of the ambient air quality network. In May 2012, the government announced the first phase of 496 monitoring stations. The first batch of cities included 74 prefecture-level cities in key regions such as Beijing, Tianjin, Hebei, Yangtze River Delta and Pearl River Delta, as well as municipalities directly under the central government and provincial capitals. The second batch of 388 monitoring stations was announced in March 2013, which included 87 prefecture-level cities such as key national environmental protection cities and model cities. The third batch, consisting of 117 other prefecture-level cities, was announced in May 2014 and contained 552 monitoring sites. In January 2015, the government announced the full rollout of the ambient air quality standards, which contain a total of 1,436 monitoring sites in 338 prefecture-level cities and above nationwide. The spatial distribution of cities implemented the new AAQS are shown in Figure 1. The announcement of ambient air quality standards has facilitated public participation in air quality monitoring, while enriching the government's means of combating air pollution and strengthening the environmental awareness of enterprises (Bai et al., 2021). As the disclosure of environmental information raises the concern of the whole society about air quality, this may change the air pollution situation especially $PM_{2.5}$ concentration.

2.3 Research hypothesis

The effective disclosure of environmental information means an increase in environmental awareness throughout society. Once the government, enterprises, and the public start to pay attention to air quality levels, they will take appropriate measures to avoid the intensification of air pollutant concentrations. In addition, the AAQS announcement process is temporally divided into four batches over a 3-year period, and the spatial distribution of monitoring sites in different batches shows a clustering of key areas to a diffusion of non-key areas. Therefore, when the AAQS monitoring points in one region are published, their suppressive effect on air pollutants may have a spatial spillover effect, thus promoting the reduction of air pollutant concentrations in neighboring areas (Wang et al., 2022a). Based on the above analysis, this paper proposes the following Hypothesis 1.

H1: Environmental information disclosure will reduce local air pollution and reduce air pollution in surrounding areas through spillover effects.

Environmental information disclosure can directly affect the concentration of pollutants in the air and may also inhibit air pollution through other pathways. On the one hand, environmental information disclosure enhances public environmental concerns and increases public awareness of environmental protection, which in turn reduces air pollution. For example, Li et al. (2022) explored the effect of public environmental concern on air pollution using air pollution data and Baidu index for prefecture-level cities in China from 2013 to 2018. They found that public environmental concern raised public dissatisfaction and public health risk concern. When concern rises, the pressure on the government starts to become greater, which ultimately promotes government measures to reduce air pollution. Ding et al. (2022) conducted a quasi-natural experiment on pollution information transparency in Chinese cities in 2008 based on the Pollution Information Transparency Index (PITI) to investigate the effect of PITI disclosure on corporate green innovation. They found that environmental information disclosure increased green patenting activities of highly polluting firms. In addition, environmental information disclosure may promote industrial upgrading. Since the tertiary sector possesses lower pollution levels than the secondary sector, once the share of the tertiary sector increases, it can effectively reduce air pollution. Liu et al. (2021b) assessed the impact of national environmental disclosure programs on regional industrial structure upgrading in 2003 and 2017. They found that environmental pollution information disclosure significantly upgraded local industrial structure and promoted ecological transformation at the city level, thereby reducing air pollution. Based on the above analysis, this paper proposes the following Hypothesis 2.

H2: Environmental information disclosure mainly reduces air pollution by enhancing public environmental concerns, green innovation, and industrial upgrading.

The effect of environmental information disclosure on air pollution reduction may also be influenced by the level of government environmental governance. It has been generally accepted in the literature that increased government environmental regulation significantly reduces regional air pollution (Ouyang et al., 2019; Wang et al., 2021c; Chen et al., 2022). Environmental information disclosure enhances public and governmental concern about air pollution issues. For regions with higher levels of environmental regulation, governments respond to public concerns by treating air pollution with more stringent standards (Wang et al., 2021c). However, for regions with lower levels of environmental regulation, environmental concerns cannot enhance the government's pollution control in the short term, so its effect on reducing air pollution is limited. Therefore, this paper proposes the following Hypothesis 3.

H3: Increased government environmental regulation will enhance the effect of environmental information disclosure on air pollution reduction.

3 Methods and data

3.1 Data

This paper selects the panel data of 269 prefecture-level cities from 2006 to 2017 as research sample, including 3,228 observations. The sample selection period covers 6 years before and after the implementation of AAQS, which is sufficient to assess the treatment effects of the policy. The data of $PM_{2.5}$ concentration comes from China's air quality online monitoring and analysis platform (https://www.aqistudy.cn/). The data of city-level control variables come from Chinese City Statistics Database (CCSD) in Chinese Research Data Services (CNRDS) Platform (https://www.cnrds.com/Home/Index#/FinanceDatabase/DB/CCSD). In this paper, cities with missing samples are excluded to maintain a balanced panel dataset to meet the estimation assumption of spatial panel model.

3.2 Econometric model

This paper uses the DID model to assess the impact of environmental information disclosure, i.e., the implementation of ambient air quality standards (AAQS), on air pollution. In addition, local air pollution will affect the air pollution in surrounding areas, and the air pollution of the previous year will also affect the air pollution level of the current year (Wang et al., 2022b; Yang et al., 2022b). Therefore, this paper incorporates spatial

TABLE 1 Descriptive statistics.

Variables		Variable description	N	Mean	Min	Max	Std
Dependent variable	ln$pm_{2.5}$	Logarithmic value of $PM_{2.5}$ concentration (μg/m³)	3,228	3.808	2.599	4.687	0.324
Independent variable	*AAQS*	Implementation of AAQS	3,228	0.402	0.000	1.000	0.490
Control variable	ln*rgdp*	GDP *per capita* (yuan)	3,228	10.352	4.595	13.056	0.710
	Eg	Environmental governance (%)	3,228	12.171	8.178	14.164	0.783
	ln*pop*	Population per unit area (km²)	3,228	5.902	3.400	8.129	0.669
	ln*bus*	Buses per 10,000 people (vehicle)	3,228	8.573	4.331	12.566	0.962
	is	Industrial structure (%)	3,228	48.961	18.420	90.970	10.092
	tem	Temperature (°C)	3,228	15.317	−2.200	23.900	5.080
	hum	Humidity (%)	3,228	68.523	40.000	85.000	9.411
	pre	Precipitation (mm)	3,228	8.115	6.394	13.816	1.834
	sun	Sunshine duration (h)	3,228	7.077	3.733	13.816	1.489

factors and dynamic effects based on the traditional DID model, and employees the dynamic spatial DID model to assess the impact of AAQS on air pollution. The econometric model is specified:

$$Y_{i,t} = \alpha + \beta_1 Y_{i,t-1} + \beta_2 \sum_{j=1}^{n} W_{i,j} Y_{i,t} + \beta_3 AAQS_{i,t} + \beta_4 \sum_{j=1}^{n} W_{i,j} AAQS_{i,t} + \beta_5 Con_{i,t} + . \beta_6 \sum_{j=1}^{n} W_{ij} Con_{i,t} + \varepsilon_{i,t} \quad (1)$$

$$AAQS_{i,t} = \begin{cases} 1, if\ AAQS\, is\, implemented\, of\, city\, i\, in\, year\, t \\ 0, if\ AAQS\, is\, not\, implemented\, of\, city\, i\, in\, year\, t \end{cases} \quad (2)$$

where $Y_{i,t}$ denotes the air pollution of city i in year t; $Y_{i,t-1}$ denotes the air pollution of city i in year t-1; $AAQS_{i,t}$ denotes the dummy of implementation of ambient air quality standards of city i in year t; Con_{it} denotes the control variables; $\sum_{j=1}^{n} W_{i,j} Y_{i,t}$ denotes the spatial lag term of air pollution; $\sum_{j=1}^{n} W_{ij} Con_{i,t}$ is the spatial lag term of control variables; $\sum_{j=1}^{n} W_{i,j} AAQS_{i,t}$ is the spatial lag term of implementation of ambient air quality standards. This paper uses a geographical inverse distance weight matrix that can simultaneously fit and explain the objective model more significantly than the direct economic distance weighting matrix and geographical weight matrix:

$$W_{i,j} = \begin{cases} e^{-\alpha d_{i,j}}, i \neq j \\ 0, i = j \end{cases} \quad (3)$$

where $W_{i,j}$ is a spatial weight matrix; α is the economic distance coefficient; $d_{i,j}$ is the economic distance between i and j. In the matrix it represents, the diagonal elements are all equal to 0.

3.3 Variables

The dependent variable in this study was air pollution. Since the main environmental monitoring index disclosed after the implementation of AAQS is $PM_{2.5}$ concentration, this paper selects the logarithmic value of $PM_{2.5}$ concentration in prefecture-level cities as a proxy variable to measure air pollution. The higher the $PM_{2.5}$ concentration, the more serious the air pollution is. The independent variable in this paper is the implementation of AAQS. According to Eq. 2, the sample after the implementation of AAQS takes the value of 1, and the sample before the implementation of AAQS takes the value of 0. Meanwhile, this paper selects a series of control variables adding into the model to assess the impact of AAQS on air pollution more reliably. The control variables selected in this paper include economic development (ln*rgdp*), the total population (ln*pop*), the number of buses (ln*bus*), the industrial structure (*is*), temperature (*tem*), humidity (*hum*), precipitation (*pre*) and sunshine duration (*Sun*) (Wu et al., 2020; Han and Miao, 2022). The measurement and descriptive statistics of each variable are shown in Table 1.

4 Results

4.1 Spatial autocorrelation test

The spatial distribution characteristics of key variables need to be analyzed before using spatial econometric model. This section analyzes the spatial distribution and spatial correlation of urban $PM_{2.5}$ concentration in China. Figure 2 reports the spatial distribution of urban $PM_{2.5}$ concentration. It can be seen that the air pollution is most severe in northern China and decreases gradually from its center to the periphery. This indicates that there is a clear spatial correlation of urban $PM_{2.5}$ concentrations in China. The scatter plot of Moran's I index can reflect the spatial correlation of urban $PM_{2.5}$ concentration more visually. Figure 3 shows the scatter plots of $PM_{2.5}$ concentration in each city in 2006, 2011 and 2017. In these three plots, the horizontal axis denotes the standardized $PM_{2.5}$ concentration and the vertical axis denotes the spatial lagged values. According to the scatter plots, the coefficients of the main fitted lines are significantly larger than zero, which indicates a positive correlation between air pollution in neighboring cities. Table 2 shows the specific results of the Moran index of urban $PM_{2.5}$ concentration. The Moran's I index is significantly positive at the 1% level during the period from 2006 to 2017. The values of Moran's I index range between 0 and 1. This indicates that urban $PM_{2.5}$ concentration have a strong spatial correlation. Thus, spatial factors should be considered in the estimation model.

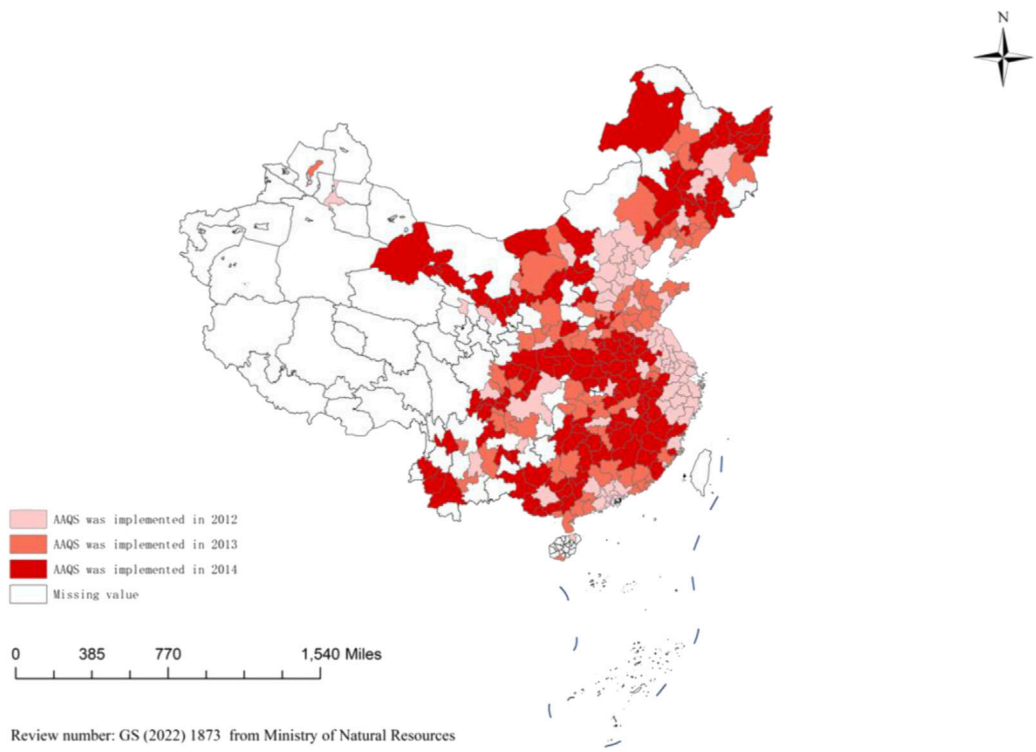

FIGURE 1
Spatial distribution of AAQS implementation cities.

4.2 Impact of environmental information disclosure on air pollution

According to the hypothesis one in Section 2.3, this paper concludes that environmental information disclosure will reduce air pollution. We adopt a dynamic spatial DID model to estimate the effect of AAQS on urban $PM_{2.5}$ concentration to test hypothesis 1. The following Table 3 reports the results. Column (1) reports the estimation results of the fixed effects model, while column (2), column (3) and column (4) report the estimation results of SEM, SLM and SDM, respectively.

The coefficient of AAQS in the estimation results based on the FE model is −0.015 ($p < 0.01$), which passes the 1% significance level test. After considering dynamic effects and spatial lag effects in the FE model, the regression coefficient of AAQS in the SLM estimation results is −0.023 ($p < 0.01$), which is also significant at the 1% level. After incorporating spatial error effects based on the FE model, the coefficient of AAQS in SEM is −0.037 ($p < 0.01$). Finally, this paper uses SDM to consider dynamic effects, spatial error effects and spatial lag effects simultaneously. The results show that the coefficient of AAQS is −0.020 ($p < 0.01$), which passes the 1% significance level test, the results coincide with Zhang et al. (2022c). This indicates that the implementation of the AAQS reduced urban $PM_{2.5}$ concentration by 2%, i.e., environmental information disclosure significantly reduced air pollution.

The detailed results for SDM are presented in Table 4, SDM further reported the direct, indirect, and total effects of AAQS on $PM_{2.5}$ concentration. The direct effect is −0.030 ($p < 0.01$), which indicates that AAQS implementation resulted in a 3% reduction in local $PM_{2.5}$ concentration. The indirect effect is −0.033 ($p < 0.1$), which indicates that AAQS implementation leads to a 3.3% reduction in $PM_{2.5}$ concentration in other areas. The total effect is −0.063 ($p < 0.01$), which indicates that AAQS implementation leads to an average reduction of 6.3% in $PM_{2.5}$ concentration in all cities nationwide.

The literature has generally supported that environmental information disclosure significantly reduces air pollution. For example, the study of Bai et al. (2021) showed that AAQS led to significant reductions in PM_{10} and NO_2 concentration in Tianjin from 2014 to 2017. The study of Zhong et al. (2021) also hold that the implementation of PITI resulted in a 0.959% reduction in urban SO_2 emissions in China, resulting in an effective reduction in air pollution. However, previous studies do not assess the impact of environmental information disclosure on $PM_{2.5}$ concentration, and further explore the spillover effect of environmental information disclosure. Our findings suggest that environmental information disclosure not only reduces local air pollution, but also has a significant spillover effect, i.e., reduces air pollution in surrounding areas. This suggests that environmental information disclosure is beneficial to different cities in the region for pollution control. Cities in the region can better improve air quality through cooperation and supervision.

4.3 Parallel trend test

The dynamic spatial DID model estimation is predicated on meeting the parallel trend assumption that there is no significant difference in $PM_{2.5}$ concentration between the treated group and control group samples before and after AAQS implementation. Figure 4 reports the

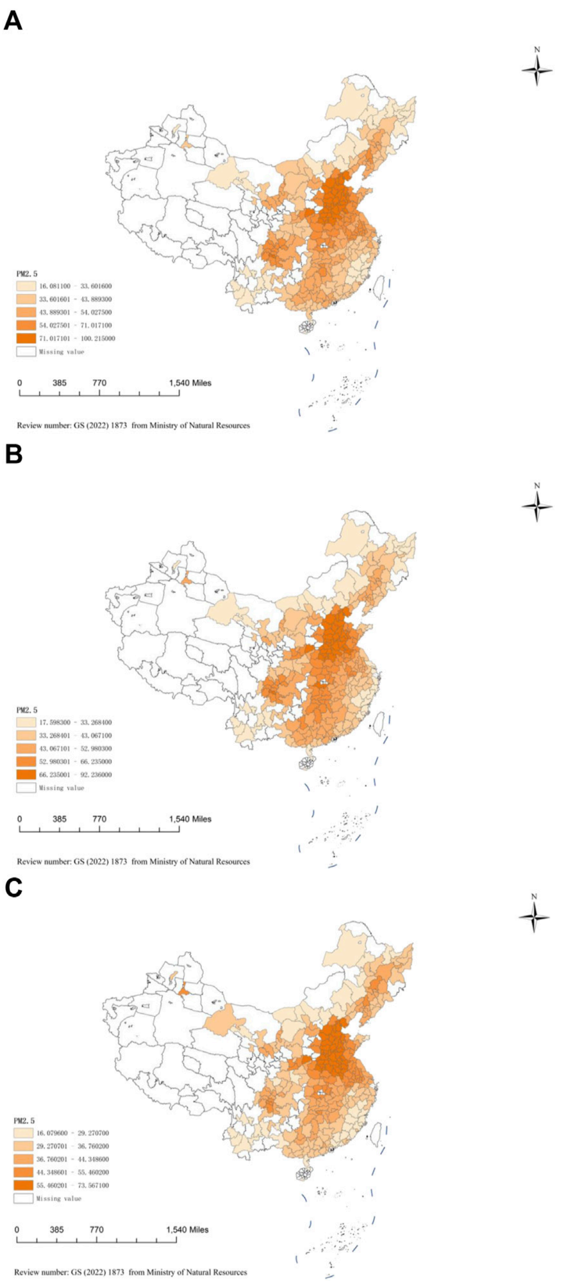

FIGURE 2
Spatial distribution of $PM_{2.5}$ concentration in China. **(A)** denotes the maps in 2006, **(B)** denotes the maps in 2011, and **(C)** denotes the maps in 2017.

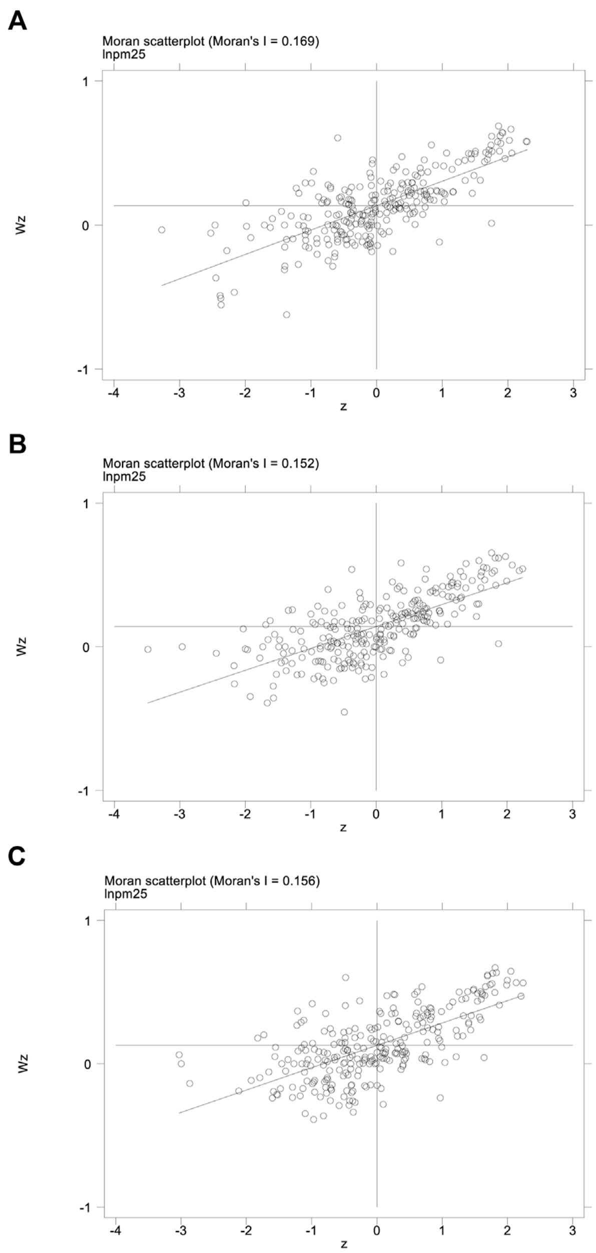

FIGURE 3
Moran scatterplot of urban $PM_{2.5}$ concentration. **(A)** denotes the Moran scatterplot in 2006, **(B)** denotes the Moran scatterplot in 2011, and **(C)** denotes the Moran scatterplot in 2017.

results of the parallel trend test. None of the regression coefficients passed the significance test prior to the implementation of the AAQS. This indicates that there was no significant difference between the control and experimental groups prior to the implementation of the policy. The hypothesis of a parallel trend was satisfied. In addition, the AAQS had the most significant effect on air pollution reduction in the first year after its implementation. However, that effect was not significant in the second and third years. By the fourth year of AAQS implementation its effect on air pollution gradually stabilized and was significantly negative. This indicates that the effect of AAQS on air pollution reduction is only significant in the short term.

TABLE 2 Calculation of Moran's I index of air pollution.

Year	Moran's I	Z-value	Year	Moran's I	Z-value
2006	0.169***	23.269	2012	0.142***	19.022
2007	0.176***	23.455	2013	0.159***	21.203
2008	0.149***	19.922	2014	0.158***	21.081
2009	0.179***	23.814	2015	0.192***	25.468
2010	0.184***	24.471	2016	0.190***	25.218
2011	0.152***	20.975	2017	0.156***	21.441

TABLE 3 Spatial spillover effects of environmental information disclosure on air pollution.

	FE	SLM	SEM	SDM
	(1)	(2)	(3)	(4)
AAQS	−0.015**	−0.023***	−0.037***	−0.020***
	(0.006)	(0.007)	(0.007)	(0.007)
l.ln$pm_{2.5}$		0.389***		0.378***
		(0.018)		(0.018)
Ln*rgdp*	−0.056***	0.000	−0.019*	0.002
	(0.006)	(0.010)	(0.010)	(0.010)
Ln*pop*	−0.180***	−0.091***	−0.193***	−0.087***
	(0.034)	(0.028)	(0.028)	(0.028)
Ln*bus*	0.028***	−0.001	0.005	−0.002
	(0.004)	(0.003)	(0.003)	(0.003)
is	0.003***	−0.002***	−0.002***	−0.002***
	(0.000)	(0.000)	(0.000)	(0.000)
tem	−0.003	0.005**	0.004*	0.005**
	(0.003)	(0.002)	(0.002)	(0.002)
hum	−0.002***	−0.001*	−0.000	−0.001
	(0.001)	(0.000)	(0.000)	(0.000)
ln*sun*	−0.012***	−0.003	−0.007***	−0.003
	(0.001)	(0.003)	(0.003)	(0.003)
ln*pre*	0.002	0.000	0.001	0.000
	(0.001)	(0.001)	(0.001)	(0.001)
wAAQS	—	—	—	−0.034**
	—	—	—	(0.014)
*w*ln*rgdp*	—	—	—	0.055***
	—	—	—	(0.019)
*w*ln*pop*	—	—	—	0.083
	—	—	—	(0.078)
*w*ln*bus*	—	—	—	−0.010
	—	—	—	(0.008)
wis	—	—	—	0.002
	—	—	—	(0.001)
wtem	—	—	—	−0.004
	—	—	—	(0.008)
whum	—	—	—	0.000
	—	—	—	(0.001)
*w*ln*sun*	—	—	—	−0.001
	—	—	—	(0.004)
*w*ln*pre*	—	—	—	0.001
	—	—	—	(0.003)

(Continued on following page)

TABLE 3 (*Continued*) Spatial spillover effects of environmental information disclosure on air pollution.

	FE	SLM	SEM	SDM
	(1)	(2)	(3)	(4)
City FE	Y	Y	Y	Y
Year FE	Y	Y	Y	Y
Observation	3228	2959	3228	2959
Log-L	216.371	2229.711	2229.711	2235.078
R^2	0.313	0.617	0.155	0.424

Note: (1) ***, **, and * denote significant at the 1% level, 5% level and 10% level. (2) City FE, and Year FE, denote the city fixed effects and year fixed effects. (3) City-level cluster robust standard errors are reported in parentheses.

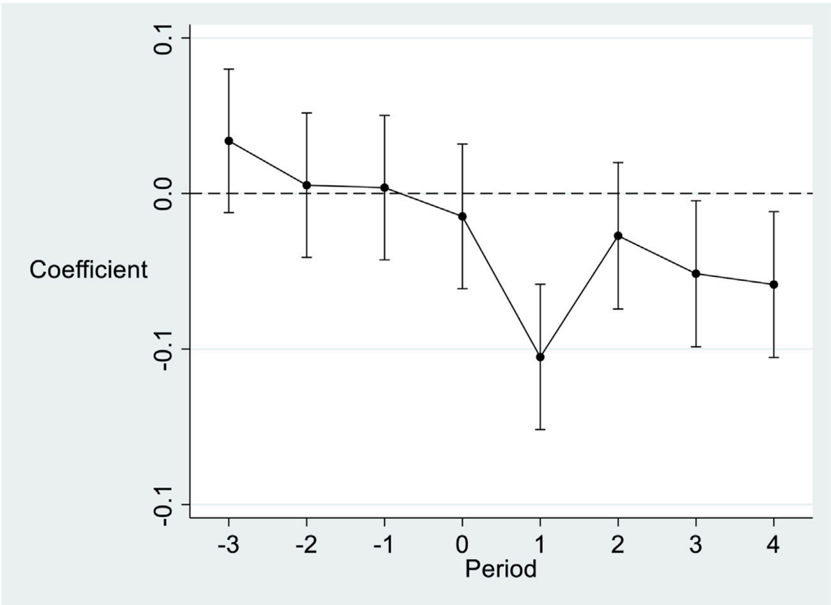

FIGURE 4
Results of Parallel Trend Test. The *X*-axis denotes the window period for AAQS implementation. The *Y*-axis represents the regression coefficient of AAQS implementation. The year before AAQS is implemented as the base period.

4.4 Further analysis

4.4.1 Mechanisms of environmental information disclosure reducing air pollution

According to the hypothesis 2, this paper argues that environmental information disclosure affects air pollution mainly through three mechanisms, which are promoting public environmental concern, green innovation, and industrial upgrading. In this section, the following mediating effects model is constructed to test each of these three mechanisms:

$$Air_{it} = \alpha + \beta AAQS_{it} + \lambda Con_{it} + \varepsilon_{it} \quad (4)$$

$$M_{it} = \alpha + \beta AAQS_{it} + \varepsilon_{it} \quad (5)$$

$$Air_{it} = \alpha + \beta AAQS_{it} + \gamma M_{it} + \lambda Con_{it} + \varepsilon_{it} \quad (6)$$

where M_{it} denotes the mediating variable, including public environmental concern, green innovation, and industrial upgrading. The data of public environmental concern are from Baidu search index. Green innovation is measured by the logarithm of the total number of green invention patents and green applicable patents of city i in year t. Industrial upgrading is measured by the ratio of tertiary sector output to secondary sector output of city i in year t. The results of the mechanism test are shown in Table 5.

According to the regressions in Table 5, the regression coefficients of AAQS in column (1), column (3) and column (5) are 1.300 ($p < 0.01$), 1.435 ($p < 0.01$) and 0.066 ($p < 0.01$), which all pass the 1% significance level test. This indicates that environmental information disclosure can significantly promote public environmental concern, green innovation, and industrial upgrading. In addition, the coefficients of epc, green_inn and iu in column (2), column (4) and column (6) are −0.009 ($p < 0.01$), −0.019 ($p < 0.01$) and −0.038 ($p < 0.05$), which all pass the 5% significance level test. Therefore, the implementation of AAQS will not only directly reduce $PM_{2.5}$ concentration, but also indirectly reduce $PM_{2.5}$ concentration by enhancing epc, green_inn and iu. Some of the literature emphasizes the importance of environmental information disclosure but does not

TABLE 4 Direct, indirect, and total effects of SDM in Table 3.

	Direct effect	Indirect effect	Total effect
AAQS	−0.030***	−0.033*	−0.063***
	(0.011)	(0.018)	(0.016)
Ln*rgdp*	0.001	0.068***	0.069***
	(0.015)	(0.025)	(0.026)
Ln*pop*	−0.147***	0.134	−0.013
	(0.044)	(0.092)	(0.096)
Ln*bus*	−0.002	−0.011	−0.014
	(0.005)	(0.010)	(0.010)
Is	−0.003***	0.003**	−0.000
	(0.001)	(0.001)	(0.001)
Tem	0.008**	−0.007	0.001
	(0.004)	(0.009)	(0.009)
Hum	−0.001*	0.001	−0.001
	(0.001)	(0.001)	(0.002)
Ln*sun*	−0.005	0.000	−0.004
	(0.004)	(0.005)	(0.006)
Ln*pre*	0.001	0.001	0.002
	(0.002)	(0.004)	(0.004)

Note: (1) ***, **, and * denote significant at the 1% level, 5% level and 10% level. (2) City-level cluster robust standard errors are reported in parentheses.

TABLE 5 Mechanisms of public environmental information disclosure reducing air pollution.

	epc	$\ln pm_{2.5}$	*green_inn*	$\ln pm_{2.5}$	*iu*	$\ln pm_{2.5}$
	(1)	(2)	(3)	(4)	(5)	(6)
AAQS	1.300***	−0.044***	1.435***	−0.034***	0.066***	−0.036***
	(0.039)	(0.009)	(0.026)	(0.007)	(0.004)	(0.007)
epc	—	−0.009**	—	—	—	—
	—	(0.004)	—	—	—	—
green_inn	—	—	—	−0.019***	—	—
	—	—	—	(0.003)	—	—
iu	—	—	—	—	—	−0.038**
	—	—	—	—	—	(0.016)
Control	Y	Y	Y	Y	Y	Y
City FE	Y	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y	Y
Observation	1758	1758	3206	3206	3228	3228
F	565.876	135.678	1261.796	191.721	2600.825	189.807
R^2	0.604	0.314	0.632	0.512	0.779	0.508

Note: (1) ***, **, and * denote significant at the 1% level, 5% level and 10% level. (2) City FE, and Year FE, denote the city fixed effects and year fixed effects. (3) City-level cluster robust standard errors are reported in parentheses.

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TABLE 6 The moderating effect of government environmental regulation.

	lnpm$_{2.5}$	lnpm$_{2.5}$	lnpm$_{2.5}$
	(1)	(2)	(3)
AAQS	−0.025***	—	−0.150***
	(0.006)	—	(0.016)
Eg	—	−0.016***	−0.011***
	—	(0.002)	(0.002)
Eg×AAQS	—	—	−0.016***
	—	—	(0.002)
C	5.222***	5.280***	4.968***
	(0.199)	(0.196)	(0.198)
Control	Y	Y	Y
City FE	Y	Y	Y
Year FE	Y	Y	Y
Observation	3228	3228	3228
F	216.371	210.534	168.740
R^2	0.268	0.269	0.292

Note: (1) ***, **, and * denote significant at the 1% level, 5% level and 10% level. (2) City FE, and Year FE, denote the city fixed effects and year fixed effects. (3) City-level cluster robust standard errors are reported in parentheses.

discuss in depth the mechanisms by which it affects pollution control (Henry and Gordon, 2003; Tu et al., 2020), they highlight the change of public behavior regarding to the environmental information and argue that the public will be more concerned, but the consequences and the mechanism are ignored. Numerous studies have shown that public environmental concern, green innovation and industrial upgrading can effectively reduce air pollution (Liu et al., 2021b; Ding et al., 2022; Li et al., 2022). This section explains the mechanisms of environmental information disclosure to reduce air pollution from the perspective of three mechanisms. The results hold that environmental information disclosure will reduce air pollution by promoting public environmental concern, green innovation, and industrial upgrading i.e., the results of the study indicate support for hypothesis 2.

4.4.2 The moderating effect of government environmental regulation

To test hypothesis 3, i.e., whether government environmental regulation enhances the effect of environmental information disclosure on the reduction of air pollution, the following model is constructed:

$$Air_{it} = \alpha + \beta AAQS_{it} + \gamma Eg_{it} \times AAQS_{it} + \lambda Con_{it} + \varepsilon_{it} \tag{7}$$

where Eg_{it} denotes level of government environmental regulation of city i in year t. $Eg_{it} \times AAQS_{it}$ denotes the interaction term between environmental information disclosure and government environmental regulation. Eg_{it} is measured by environmental word frequency. According to the study of Chen et al. (2018), this paper manually collected the text of government work reports from 2006 to 2017 from each prefecture-level city and extracted the reports and processed them by word separation. In this paper, the number of total words and the number of environment-related words in the government reports of each prefecture-level city were counted separately, and the local level of environmental regulation was measured by the proportion of the number of occurrences of environment protection-related words to the total number of words. The words related to the environment include environmental protection, green, pollution, emission reduction, *etc.* The test results of the above model are shown in Table 6.

According to the results in Table 6, the coefficient of AAQS in column (1) is −0.025 (p < 0.01) and coefficient of Eg in column (2) is −0.016 (p < 0.01), which both pass the 1% significance level test. This suggests that both environmental information disclosure and government environmental regulation can significantly reduce air pollution, and we can further test the moderating effect of government environmental regulation. The coefficient of Eg×AAQS is −0.016 (p < 0.01), which passes the 1% significance level test. The results hold that increased government environmental regulation significantly enhances the effect of environmental information disclosure on reducing air pollution, which is consistent with hypothesis 3. Although previous literature has also emphasized the importance of government environmental regulation in reducing air pollution, it has ignored its moderating effect on environmental information disclosure (Feng et al., 2020; Chen et al., 2022). As a complement to formal environmental regulation, environmental information disclosure and government environmental regulation have complementary effects (Ouyang et al., 2019; Wang et al., 2021a). The findings of this paper suggest that government environmental regulation has a positive moderating effect. Therefore, while environmental information disclosure should be

TABLE 7 Heterogeneity analysis.

	Region	Heating area	Administrative rank
	(1)	(2)	(3)
l.lnpm$_{2.5}$	0.356***	0.325***	0.377***
	(0.018)	(0.018)	(0.018)
AAQS	−0.024***	−0.044***	−0.021***
	(0.008)	(0.007)	(0.007)
AAQS×Central	0.023***	—	—
	(0.006)	—	—
AAQS×Western	−0.009	—	—
	(0.007)	—	—
AAQS×Heating	—	0.035***	—
	—	(0.006)	—
AAQS×Rank	—	—	0.006
	—	—	(0.008)
lnrgdp	0.004	0.013	0.002
	(0.010)	(0.010)	(0.010)
lnpop	−0.092***	−0.040	−0.090***
	(0.028)	(0.028)	(0.028)
lnbus	−0.004	0.000	−0.002
	(0.003)	(0.003)	(0.003)
is	−0.002***	−0.001***	−0.002***
	(0.000)	(0.000)	(0.000)
tem	0.005**	0.003	0.005**
	(0.002)	(0.002)	(0.002)
hum	−0.001**	0.000	−0.001
	(0.000)	(0.000)	(0.000)
lnsun	−0.003	−0.003	−0.003
	(0.003)	(0.003)	(0.003)
lnpre	0.001	0.001	0.000
	(0.001)	(0.001)	(0.001)
wAAQS	−0.025	−0.022	−0.033**
	(0.018)	(0.016)	(0.015)
wAAQS×Central	−0.028*	—	—
	(0.016)	—	—
wAAQS×Western	−0.003	—	—
	(0.019)	—	—
wAAQS×Heating	—	−0.026	—
	—	(0.016)	—
wAAQS×Rank	—	—	−0.004
	—	—	(0.018)

(Continued on following page)

TABLE 7 (*Continued*) Heterogeneity analysis.

	Region	Heating area	Administrative rank
	(1)	(2)	(3)
wlnrgdp	0.048**	0.031*	0.055***
	(0.019)	(0.019)	(0.019)
wlnpop	0.078	−0.045	0.085
	(0.077)	(0.078)	(0.078)
wlnbus	−0.006	−0.007	−0.010
	(0.008)	(0.008)	(0.008)
wis	0.002*	0.001	0.002
	(0.001)	(0.001)	(0.001)
wtem	−0.004	−0.007	−0.004
	(0.007)	(0.007)	(0.008)
whum	0.000	−0.001	0.000
	(0.001)	(0.001)	(0.001)
wlnsun	−0.000	−0.000	−0.001
	(0.004)	(0.004)	(0.004)
wlnpre	0.001	−0.001	0.001
	(0.003)	(0.003)	(0.003)
City FE	Y	Y	Y
Year FE	Y	Y	Y
Observation	2959	2959	2959
R^2	0.389	0.602	0.409

Note: (1) ***, **, and * denote significant at the 1% level, 5% level and 10% level. (2) City FE, and Year FE, denote the city fixed effects and year fixed effects. (3) City-level cluster robust standard errors are reported in parentheses.

continuously promoted, government environmental regulation should also be enhanced to reduce air pollution more effectively.

4.5 Heterogeneity analysis

There are huge differences in the level of economic development between regions in China, with the eastern region being higher than the central and western regions (Yu et al., 2021). Regions with higher levels of economic development have higher levels of education and complete their industrial upgrading earlier (Zhang et al., 2022a). The effect of environmental information disclosure on reducing air pollution may be stronger than that of regions with lower levels of economic development. Therefore, it is necessary to analyze the differences in the effects of AAQS implementation on air pollution in different regions. In addition, coal-fired heating is one of the important factors affecting urban $PM_{2.5}$ concentration (Yu et al., 2021). Therefore, a distinction should also be made between heating and non-heating areas when exploring the effect of AAQS implementation on urban $PM_{2.5}$ concentration. According to the study of Yu et al. (2021), the heating area is north of Qinling and Huaihe River, and the non-heating area is south of Qinling and Huaihe River. In this paper, we further investigate the differences in the effects of AAQS implementation on air pollution between heating and non-heating area. Finally, cities with higher administrative ranks have richer educational resources and innovative technologies, and their marginal effects on air pollution may be diminishing (Yu et al., 2021; Ding et al., 2022). As a result, the impact of AAQS may differ across different cities. Therefore, differences among cities with different administrative ranks should be considered when assessing the impact of AAQS implementation on $PM_{2.5}$ concentration. The results of heterogeneity analysis are shown in Table 7.

According to the results in Table 7, the regression coefficient of AAQS×Central in column (1) is 0.023, which passes the 1% significance level test. The effect of AAQS on air pollution in the central region is significantly lower than that in the eastern region, with a reduction effect of only 0.1%. The regression coefficient of AAQS×Western is −0.009, which does not pass the 10% significance level test, indicating that there is no significant difference between the effects of AAQS on air pollution in the eastern and western regions. The coefficient of AAQS×Heating in column (2) is 0.035, which passes the 1% significance level test. This indicates that AAQS can significantly reduce $PM_{2.5}$ concentration in non-heating areas by 4.4%. For heating zones, the effect of AAQS implementation on

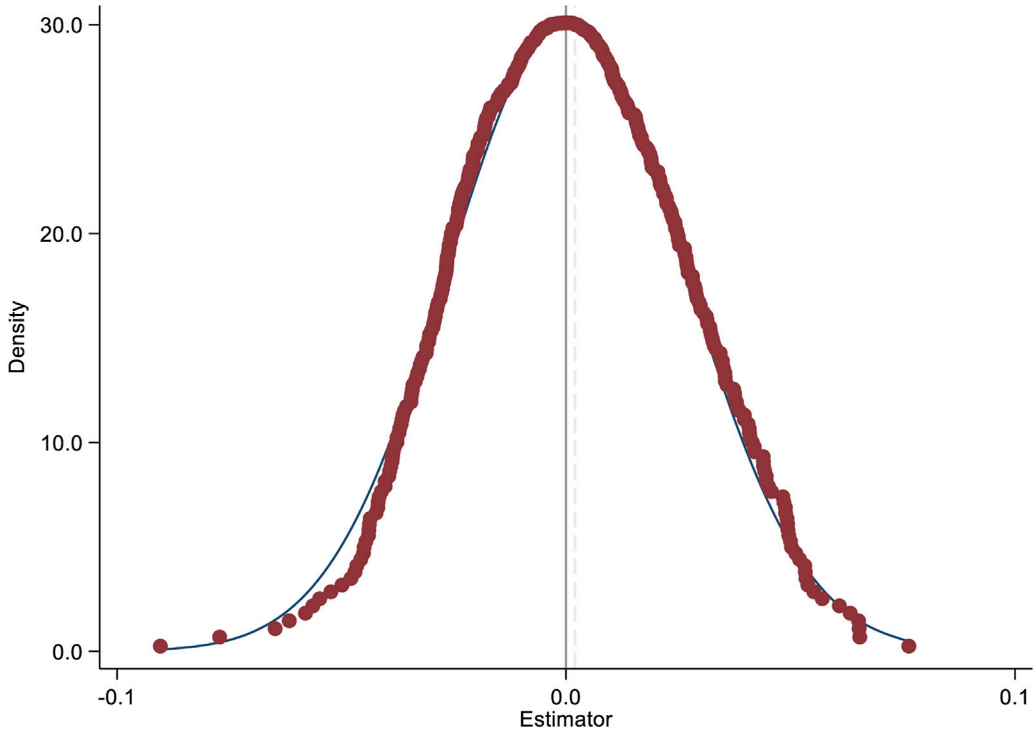

FIGURE 5
Results of placebo test. Treated group is randomly drawn 500 times in the control group by Monte Carlo simulation and DID regression was performed. Plot the obtained regression coefficients as a distribution graph. This figure reports the results of $PM_{2.5}$ concentration of cities without environmental information disclosures as a dependent variable, presenting a normal distribution with an average value of 0.

$PM_{2.5}$ concentration reduction is only 0.9%. In column (3), the coefficient of AAQS×Rank is 0.006, which fails to pass the 10% significance level test. This indicates that the effect of AAQS on air pollution does not differ significantly among cities at different administrative levels.

Our findings suggest that the effect of environmental disclosure on air pollution differs significantly across economic development levels and heating and non-heating zones. This is more consistent with the study of Yu et al. (2021), whose findings suggest that the impact of coal-to-gas policy on air pollution differs significantly between the eastern, central and western and the heating and non-heating areas. This paper argues that the main factors that lead to differences in the impact of environmental information disclosure in different regions are influenced by education level and technology level. Higher education levels can lead to stronger public environmental concerns, thus amplifying the effect of environmental information disclosure on air pollution reduction (Gu et al., 2021). Unlike Liu et al. (2021b), our results does not show statistical difference in terms of heterogeneity in administrative rank of cities. Although the EID is not directly environmental regulation in China, however, as the concentration of $PM_{2.5}$ is relatively high, the government may directly intervene and force related firms to reduce their pollutant emission since the data is public. Meanwhile, the public is also informed, they may also pressure local governments in improving air quality. As a result, the impact of EID is statistically indifferent for cities with different administrative rank.

4.6 Robustness

4.6.1 Placebo test

Since the implementation of AAQS may also affect urban $PM_{2.5}$ concentration that do not make environmental information disclosures, this may reduce the reliability of the estimation results. Therefore, this paper adopts Monte Carlo simulation to conduct a placebo test, and the results are shown in Figure 5. This paper randomly selected samples from the control group multiple times as the treated group. Then, this paper uses the DID model for re-estimation and extracts the estimated parameters. The analysis results in this paper are reliable if the estimated parameters are normally distributed and have a mean value of 0. The estimated coefficient distributions and kernel density curves after 500 random samples are given in Figure 5. As expected from the placebo test, the estimated coefficients show a normal distribution with a mean around 0. This indicates that the reduction in $PM_{2.5}$ concentration in the treated group came from the implementation of the AAQS.

4.6.2 Re-estimation based on PSM-DID

To ensure that the sample selection bias does not affect the reliability of the conclusions in this paper, we use the difference-in-difference model after propensity score matching (PSM-DID) for re-estimation. The results of PSM-DID are shown in the following Table 8.

According to the regression results in Table 8 above, the regression coefficients of *AAQS* in columns (2) and (4) were −0.014 ($p < 0.05$)

TABLE 8 Re-estimation based on PSM-DID.

	Neighbor matching		Kernel matching	
	(1)	(2)	(3)	(4)
AAQS	−0.002	−0.014**	−0.015**	−0.022***
	(0.007)	(0.007)	(0.006)	(0.006)
l.ln$pm_{2.5}$	—	0.406***	—	0.405***
	—	(0.021)	—	(0.019)
ln***rgdp***	−0.081***	−0.047***	−0.058***	−0.034***
	(0.008)	(0.009)	(0.006)	(0.007)
ln***pop***	−0.124***	−0.043	−0.167***	−0.053
	(0.039)	(0.038)	(0.036)	(0.035)
ln***bus***	0.026***	0.014***	0.029***	0.017***
	(0.004)	(0.004)	(0.004)	(0.004)
is	0.004***	0.003***	0.002***	0.002***
	(0.000)	(0.001)	(0.000)	(0.000)
tem	−0.009***	−0.005	−0.007**	−0.003
	(0.003)	(0.003)	(0.003)	(0.003)
hum	−0.002***	−0.003***	−0.002***	−0.003***
	(0.001)	(0.001)	(0.001)	(0.001)
ln***sun***	−0.012***	−0.010***	−0.013***	−0.011***
	(0.001)	(0.001)	(0.001)	(0.001)
ln***pre***	0.001	0.001	0.002	0.001
	(0.001)	(0.001)	(0.001)	(0.001)
C	5.362***	3.071***	5.347***	3.006***
	(0.237)	(0.265)	(0.216)	(0.241)
City FE	Y	Y	Y	Y
Year FE	Y	Y	Y	Y
Observation	2459	2276	2954	2688
F	134.059	169.553	138.517	183.438
R^2	0.356	0.459	0.318	0.432

Note: (1) ***, **, and * denote significant at the 1% level, 5% level and 10% level. (2) City FE, and Year FE, denote the city fixed effects and year fixed effects. (3) City-level cluster robust standard errors are reported in parentheses.

and −0.022 ($p < 0.01$), respectively, both of which passed the 5% significance level test. The PSM-DID based on nearest neighbor matching with kernel density matching obtained the same conclusion as Table 3. This indicates that environmental information disclosure can have a reduction in air pollution, i.e., the results of the previous analysis are robust.

4.6.3 Re-estimation excluding other policy disturbances

To exclude the interference of other contemporaneous policies on the analysis results, this paper further controls for the policy shocks of Pollution Information Transparency Index (PITI), Low Carbon City Pilot (LCCP), Carbon Emission Trading Pilot (CETP) and Air Pollution Prevention and Control Program (APCP) in the model (Feng et al., 2019; Cui et al., 2021; Zhang et al., 2022a). The results of the effects of AAQS on urban $PM_{2.5}$ concentration after adding the above four policy shocks are shown in Table 9.

According to the results in Table 9, the regression coefficients of AAQS in columns (1) to (4) are −0.024 ($p < 0.01$), −0.022 ($p < 0.01$), −0.023 ($p < 0.01$) and −0.023 ($p < 0.01$), respectively, all of which pass the 1% significance level test. This indicates that the effect of AAQS on the reduction of urban $PM_{2.5}$ concentration remains robust after considering the contemporaneous policies. Therefore, environmental information disclosure can effectively reduce air pollution.

TABLE 9 Re-estimation excluding other policy disturbances.

—	(1)	(2)	(3)	(4)
$l.lnpm_{2.5}$	0.392***	0.390***	0.392***	0.394***
	(0.018)	(0.018)	(0.018)	(0.018)
AAQS	−0.024***	−0.022***	−0.023***	−0.023***
	(0.006)	(0.006)	(0.006)	(0.006)
PITI	−0.013**	—	—	—
	(0.006)	—	—	—
LCPC	—	−0.011*	—	—
	—	(0.006)	—	—
CETC	—	—	0.002	—
	—	—	(0.008)	—
APCP	—	—	—	0.017*
	—	—	—	(0.010)
C	3.161***	3.048***	3.087***	3.031***
	(0.233)	(0.231)	(0.232)	(0.232)
City FE	Y	Y	Y	Y
Year FE	Y	Y	Y	Y
Observation	2959	2959	2959	2959
F	175.100	174.857	174.415	174.871
R^2	0.418	0.418	0.417	0.418

Note: (1) ***, **, and * denote significant at the 1% level, 5% level and 10% level. (2) City FE, and Year FE, denote the city fixed effects and year fixed effects. (3) City-level cluster robust standard errors are reported in parentheses.

5 Conclusion and discussion

5.1 Conclusion

Through a dynamic spatial DID model, this paper uses AAQS as a quasi-natural experiment to assess the impact of environmental information disclosure on air pollution. Through empirical analysis, we obtain the following three conclusions. First, implementation of the AAQS resulted in a 3% reduction in local $PM_{2.5}$ concentration and a 3.3% reduction in $PM_{2.5}$ concentration in surrounding areas. The total reduction effect of the AAQS on $PM_{2.5}$ concentration in the sample cities was 6.3%. Our findings suggest that environmental information disclosure not only reduces local air pollution, but also has significant spillover effects. Second, this paper further explores the mechanism by which environmental information disclosure affects air pollution. Our findings suggest that environmental information disclosure reduces air pollution by enhancing public environmental concerns, green innovation, and industrial upgrading. In addition, we examine the externalities of government environmental regulation using a mediating effects model. The findings hold that the increase in government environmental regulation enhances the effect of environmental information disclosure on air pollution reduction. Third, the results of the heterogeneity analysis show that the effect of environmental information disclosure on air pollution varies across regions. In terms of economic development level, the reduction effect of environmental information disclosure on air pollution is strongest in the more developed eastern region. The effect of environmental information disclosure on air pollution in the central region is significantly lower than that in the eastern region. In addition, the reduction effect of environmental information disclosure on air pollution in non-heating areas is much higher than that in heating areas. We also performed a series of robustness tests to ensure the reliability of the findings, including placebo tests, re-estimation based on PSM-DID, and the re-estimation excluding contemporaneous policy interference. The robustness tests yielded consistent conclusions.

This paper contributes to current literature in the following aspects. First, we investigate the impact of EID on air quality with a quasi-natural experiment in China, the implementation of the new Ambient Air Quality Standards helps us better identify the causal inference. And the spatial DID model is employed to identify the spatial spillover effect. Second, we further investigate the impact mechanism between EID and air quality which has rarely been explored in current studies. Three channels are investigated: public environmental concern, green innovation, and industrial upgrading. Finally, the heterogeneity of cities is considered, including location, heating approach, and the administrative rank.

5.2 Discussion

Based on the findings of the study, this paper proposes the following three recommendations. First, government should further develop the scope and quality of environmental quality information disclosure. Findings of this paper show that environmental information disclosure can significantly reduce urban air pollution. Therefore, the state should speed up the introduction of mandatory environmental information disclosure rules for wastewater, waste gas, and other areas in various environmental protection areas where technical conditions and cost inputs allow. It is also important to disclose environmental quality indicators that have a greater impact on residents' health and social welfare to the society and to improve the quality of environmental information data disclosure. These measures can effectively promote public participation in regional pollution prevention and control and enhance the construction of a shared governance system for environmental governance. Second, the government should expand the impact of environmental information disclosure by enhancing public awareness of environmental protection, encouraging enterprises to engage in green innovation, and promoting the clustering of high-tech industries. Enterprises should make full use of the preferential policies for green development, improve their R&D capabilities, and accelerate the pace of green transformation. Only by turning the pressure of pollution reduction into the motivation of upgrading, the internal upgrading from polluting production to clean production can be completed. The local government should provide more support for the green transformation of enterprises and provide necessary support during the transition period. Finally, the government should construct a cross-regional synergistic system for pollution prevention and control. The findings of this paper suggest that there is a spatial spillover effect of environmental information disclosure on air pollution. Long-term sustainable environmental protection policies must be able to mobilize regional initiatives for green development. An ecological compensation system based on the effectiveness of pollution prevention and control can enable regions with different levels of economic development to continuously improve the quality of the regional ecological environment. Cities in the region should provide timely feedback on the process and results of environmental pollution events based on the regional environmental quality information platform.

This paper highlights the important role of environmental information disclosure in improving air quality. However, there are still some limitations in this paper. Our data only contains city-level sample, not firm-level sample. However, firms are the entities of air pollution, thus, the conclusion will be more precise if firm-specific data is employed. Moreover, the impact of EID should differ across different industries, existing data does not provide this difference. As a result, for future research, one can complete the dataset with firm-level samples, which will precisely identify the firm- and industry-specific heterogeneity.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: Chinese City Statistics Database (CCSD) in Chinese Research Data Services (CNRDS) Platform (https://www.cnrds.com/Home/Index#/FinanceDatabase/DB/CCSD).

Author contributions

LX, HL contributed to conception and design of the study. ZW organized the database. XZ performed the statistical analysis. CY wrote the first draft of the manuscript.

Funding

LX acknowledges the financial supports sponsored by the National Social Science Foundation of China (Grant No. 20CJY040) and the Scientific Research Foundation of Chongqing University of Technology.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 28 February 2023
DOI 10.3389/fenvs.2023.1090998

OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Environmental Economics and Management, a section of the journal Frontiers in Environmental Science

RECEIVED 06 November 2022
ACCEPTED 20 February 2023
PUBLISHED 28 February 2023

CITATION
Gao C, Cao M, Wen Y and Li C (2023), Coupling and interaction between science and technology finance and green development: Based on coupling coordination degree model and panel vector autoregression model.
Front. Environ. Sci. 11:1090998.
doi: 10.3389/fenvs.2023.1090998

Coupling and interaction between science and technology finance and green development: Based on coupling coordination degree model and panel vector autoregression model

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Exploring the coupling and coordination between science and technology finance and green development is a critical action that needs to be addressed in achieving high-quality development in China. Based on the coupling coordination degree model and panel vector autoregression (PVAR) model, this paper uses the relevant data of 274 cities in China from 2003 to 2020 to study the relationship between science and technology finance and green development. The results show that: 1) The relationship between science and technology finance and green development has changed from low coupling coordination to medium coupling coordination in the sample period. 2) The Beijing-Tianjin-Hebei, Yangtze River Delta, and Pearl River Delta regions are at a relatively high level of coupling and coordination as a whole, while other regions are at a relatively low level of coupling and coordination. 3) Through the analysis of the spatial characteristics of the coupling coordination degree, it is found that the coupling coordination degree of China's urban science and technology finance and green development is generally positive spatial autocorrelation. Spatial correlations continue to strengthen over time. 4) By establishing a PVAR model, we examined the interaction between science and technology finance, green development, and their coupling coordination. Science and technology finance, green development and their coupling coordination degree are themselves affected. We have comprehensively and objectively grasped the matching status of China's urban science and technology finance and green development, providing a reference for promoting the adaptation of science and technology finance to green development.

KEYWORDS

science and technology finance, green development, coupling coordination degree, spatial effect, PVAR model

1 Introduction

Climate and global warming have emerged as significant issues facing people worldwide. Numerous scholars have studied economic development, financial development, energy consumption, and carbon dioxide emissions and obtained valuable results (Mitić et al., 2023; Usman et al., 2022; Cheng et al., 2023; Khan, 2023). Scientific and technological innovation is the first driving force of green development and is crucial to promoting the construction of ecological civilization (Cao et al., 2021). Since the 1980s, a new round of scientific and technological innovation represented by information, network, digital, and biotechnology has provided technical support and fundamental guarantee for the development of a green economy (Kim, 2019). The role of information technology in economic and social progress has long been recognized (Rehman et al., 2022). As a development mode with less environmental pollution, low energy consumption, and high scientific and technological content, green development cannot be achieved by relying solely on traditional production methods. It must rely on scientific and technological innovation (Dunn, 2002; Aqib and Zaman, 2023). The 2020 Green Development Science and Technology Innovation Conference, with the theme of "enabling green development through digital economy," emphasized the relationship between scientific and technological innovation and green development. The conference proposed that high-quality green development must be led and supported by science and technology. However, an essential institutional problem in China's current scientific and technological development is the lack of a long-term stable source of capital (Wu et al., 2021).

Many scholars have studied the impact of scientific and technological innovation on the ecological environment using the IPAT or STIRPAT method (Dietz and Rosa, 1994; York et al., 2003). Regardless of the form of technological innovation, it affects energy efficiency through technology spillover effects. Most studies showed that technological progress can improve energy efficiency (Lin and Moubarak, 2014; Sun et al., 2019). However, some scholars believe scientific and technological innovation negatively related with energy efficiency (Hübler and Keller, 2010; Adom and Amuakwa-Mensah, 2016). Nathaniel et al. (2021) believed that technological innovation could directly improve environmental quality *via* developing technologies related to environmental protection. Usman and Hammar (2021) believed that technological innovation was not conducive to improving environmental quality. As technological innovation optimizes the ecological footprint of the region, the ecological environment is more vulnerable to damage. These findings may be due to different methods and sample data selected by the scholars.

Technological innovation, financial markets and their combinations are playing an increasingly important role in economic construction and social progress (Perrons, 2004). How to accelerate the development of science and technology finance, promote independent innovation and achieve high-quality economic growth has become a hot issue in recent years (Gao et al., 2022). Huang (2019) used the VAR model to investigate the relationship between science and technology finance and economic growth in Shanghai based on the data of Shanghai's science and technology finance investment and high-tech industry output value from 2004 to 2016. He found that investment in science and technology finance is conducive to raising the output value of high-tech industries. Therefore, the Shanghai municipal government should increase the investment in scientific and technological financial capital to deepen the positive role of science and technology finance in the development of high-tech industries. Hua et al. (2021) employed the entropy weight method and super efficiency DEA model to measure China's science and technology finance index and ecological efficiency, respectively, then constructed a spatial econometric model to empirically analyze the influence of science and technology finance on regional ecological efficiency. The study denoted that science and technology finance and industrial structure optimization have failed to effectively optimize ecological efficiency. Financial development can only exert positive spillover impact on ecological efficiency under the supervision of industrial structure optimization.

The profit-seeking nature of capital makes it difficult for scientific and technological financial resources to break this law. In their pursuit of maximizing economic benefits, they often neglect the governance of the ecological environment. In addition, China's scientific and technological financial development is still in its infancy, and the overall level is not high. The combination of science, technology and finance plays a more critical role in the efficiency of production technology than environmental protection. At least some technologies have not yet achieved the transformation of green achievements, but may have a negative impact on the environment (Asche et al., 2009). Shi and Xia (2022), based on the perspective of the industrial life cycle, adopted the Logistic model to analyze the impact of science and technology finance in 11 provinces and cities of the Yangtze River Economic Belt on the development of high-tech industries. They found that science and technology resources, market financing and government investment in science and technology are crucial channels for science and technology finance to stimulate the development of high-tech industries. The development of high-tech industries in the middle and lower reaches of the Yangtze River Economic Belt requires more financial innovation tools to support it.

Several scholars have studied technology finance in terms of coupling relations. Zhou and Feng (2020) investigated the coupling and interaction between science and technology finance and high-quality economic development in 31 provinces of China. They noted that science and technology finance and high-quality economic development had improved from 2008 to 2017, and the coupling degree between them showed a steady upward trend. In terms of interaction, high-quality economic development has significantly boosted the development of science and technology finance. In contrast, science and technology finance has no significant influence on high-quality economic development. Liu et al. (2021) studied the dynamic coupling nexus between sci-tech finance and advanced manufacturing innovation in 30 provinces of China during 2007–2019. They proposed that the degree of coupling coordination in each region shows a trend of continuous optimization overall, but there are differences in the degree of coupling in different regions. Feng et al. (2022) explored the coupling relationship between science and technology finance and industrial structure in China using the coupling model. They found that the two couplings exhibit an overall upward trend, but there are large differences in each region, with the mean value of the couplings decreasing successively from east to west.

In order to promote the balanced and coordinated development of science and technology finance and urban green development, this paper examines the coupling mechanism of science and technology finance and green development from the elements of the comprehensive indicator system of science and technology finance and green development. The culmination of this paper will not only help governments formulate scientific and sound policy recommendations but will also be of the great reference value and practical importance for countries around the world to build a new development model and promote high-quality economic and social development.

The main contributions are as follows: First, there are still significant differences in the construction of this metric as different scholars have not yet reached a consensus on the understanding of science and technology finance. In this paper, we will construct a comprehensive index of science and technology finance based on existing research and multiple dimensions. At the same time, a comprehensive system of indicators for green development will be established based on four levels of economic growth, social welfare, ecological construction, and institutional provision. Second, from the coupling perspective, we use the coupling coordination degree model to calculate the coupling coordination between science and technology finance and green development. Then, we use the PVAR model to investigate their dynamic relationship. This paper addresses the lack of empirical evidence on the relationship between science and technology finance and green development. Finally, this paper provides empirical evidence for city-level data with a larger sample size.

The remainder of this study is organized as follows: Section 2 describes the system coupling mechanism of science and technology finance and green development. Section 3 provides the methodology, which mainly introduces variables and model settings. Section 4 reports the results and discussion. Section 5 includes the conclusion and policy recommendations of this study.

2 The system coupling mechanism of science and technology finance and green development

There is no unified definition of "science and technology finance," and most of the literature only focuses on scientific and technological innovation and financial support. The first domestic proposal of "science and technology finance" was in the Law of the People's Republic of China on Science and Technology Progress in 1993. Subsequently, Zhao et al. (2009)'s definition of "science and technology finance" was recognized by some scholars. Science and technology finance is a systematic arrangement of financial systems, policies and tools to facilitate the transformation of the achievements, research and development of science and technology and high-tech industries. Therefore, based on the existing research, this paper will judge the development of science and technology finance in four aspects: resources, funding, financing and output. In addition, according to the contents of the "14th Five Year Plan" and the outline of the 2035 long-term goals, green development involves many aspects. This paper will analyze the coupling mechanism between regional science and technology finance and green development from the perspective of ecological construction, economic development, social welfare and institutional supply, as shown in Figure 1.

2.1 Science and technology finance promotes green development

As the two most active factors in economic and social development, the combination of technology and finance has transformed the development mode from factor-driven to innovation-driven (Xu, 2022). Science and technology are the primary productive forces. Scientific and technological advances require financial support. Continuously improving the combination of science, technology, and finance is significant for promoting independent innovation and improving total factor productivity (Xue et al., 2022). Due to the lack of direct research on the impact of science and technology finance on green development, this paper analyzes the impact of science and technology finance on green development in four dimensions. The detailed analysis proceeds as follows.

Firstly, some scholars believe that traditional technologies will lead to excessive energy use and increase carbon emissions, leading to the deterioration of environmental quality (Jin et al., 2014). Advances in traditional technologies are essential in environmental pollution, and developing green technologies is imminent. The progress of green technology is an important means to improve environmental quality, which indicates that government departments need to pay more attention to green technology innovation to achieve environmental governance effect (Hou et al., 2022). The development of green technologies requires strong support from financial development, and the deep integration of science and technology with finance provides the necessary material foundation for urban ecological construction.

Secondly, according to Solo's economic growth model, technological progress is a crucial factor in promoting a country's economic growth, which has also been recognized by many scholars (Coe and Helpman, 1995; Brouhel and Thierer, 2019). At the same time, financial development can not only mitigate the financing constraints of high-tech industries, but also support enterprise R&D innovation, thus promoting economic growth (Hu et al., 2017). Therefore, the effective combination of scientific and technological innovation and financial development plays a vital role in economic construction.

Third, science and technology finance can improve the economic development of cities and thus increase the total social wealth. The local government can get more income from it and master more resources to increase the investment in education, medical care, transportation, commercial support, etc. At the same time, the government will inject more resources into the social security system as the level of social income rises. After the basic life of residents is guaranteed, they will turn to human capital investment, which not only brings positive externalities to create a favorable economic environment but also improves the innovation ability of the whole society (Stahl et al., 2020). As a result, scientific and technological innovation promotes social wellbeing by increasing wealth.

Fourth, institutional regulations mainly include infrastructure and environmental governance. On the one hand, with the iteration of cutting-edge technologies such as blockchain, cloud computing and big data, the economic environment will develop in-depth and intelligently, which is bound to drive the rapid development of regional infrastructure (Su et al., 2021). On the other hand, the role of science and technology finance in environmental governance. Science and technology finance has been incorporated into national strategic planning related to the country's overall stability. Green development puts higher demands on the development of green industries and innovation in green technology, thus constantly pushing local governments to improve their environmental governance systems.

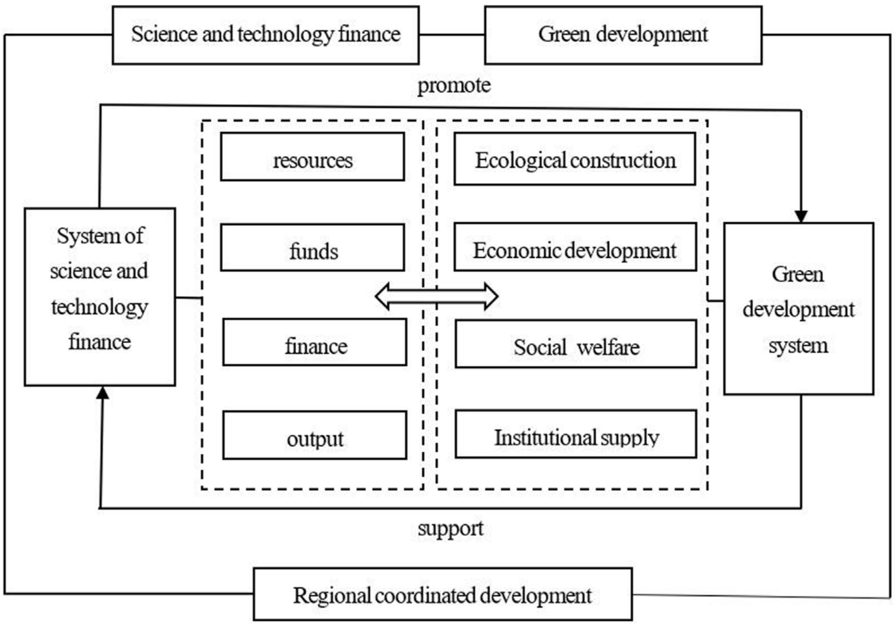

FIGURE 1
Coupling mechanism between science and technology finance and green development.

2.2 Green development supports science and technology finance

First, green development will encourage local governments to increase investment in green innovation R&D projects for technology-based enterprises, especially bringing high-quality infrastructure, innovative R&D capital, and other elements for small and medium-sized technology-based enterprises (Chen et al., 2017). The increasing accumulation of resources, such as talent, knowledge and technology, provides necessary material guarantees and convenient conditions for scientific and technological enterprises in the research and development process. The accumulation of human capital has improved the overall efficiency of the innovation system of science and technology finance and injected new impetus into the development of science and technology finance (Bergek et al., 2013).

Second, green development creates broader market demand for the development of science and technology finance and helps improve the environment for science and technology finance. To achieve the goal of green development, rational development, optimization and upgrading traditional industrial structures is imperative. In this process, financial innovation is indispensable to provide more market demand for developing science and technology finance (Irfan et al., 2022). At the same time, the development of science and technology finance is often based on the traditional financial industry, which significantly impacts the development of traditional industries. In recent years, China's economic development model has undergone significant changes, and traditional forms of financing, dominated by banks, are no longer applicable. The future financing system should be a diversified form dominated by the market mechanism and combined with direct financing and indirect financing, which broadens the financing channels of scientific and technological enterprises and improves the scientific and technological financial environment (Zhao, 2008).

Finally, green development provides an excellent institutional environment for science and technology finance and avoids risks to developing the science and technology finance industry. Governments at all levels have formulated many green development policies and plans, which will create necessary constraints and guarantees for scientific and technological financial activities to avoid risk sources in scientific and technological development (ElMassah and Mohildin, 2020). At the same time, green development can drive institutional innovation and promote the continuous improvement of the legal system related to science and technology finance. The steady development of the regional economy and the stability of financial markets have provided guarantees for the development of science and technology finance. Based on the analysis of the theoretical mechanism described above, we propose the following research hypothesis.

Hypothesis 1: There is a coordinated development relationship between science and technology finance and green development.

Hypothesis 2: There is an interactive causal relationship between science and technology finance and green development.

3 Methodology

3.1 Indicator system

3.1.1 Indicator system of science and technology finance

Scholars have not precisely defined "science and technology finance" (Ma et al., 2013). Currently, most research is conducted from the perspective of scientific and technological innovation, financing, and financial support. "Science and technology finance" was first proposed in the Law of the People's Republic of China on Science and Technology Progress in 1993. In recent years, numerous scholars have adopted different methods to build the indicator system of science and technology finance (Cao et al., 2011; Xu et al., 2015; Wang et al., 2022). This paper constructs a comprehensive indexing system for science and technology finance from four aspects: resources, funding, financing, and output.

Financial resources for science and technology include: Human resources for science and technology are measured as the ratio of the number of scientific and technological personnel to the total population of the region at the end of the year. R&D personnel, as measured by the proportion of R&D personnel in the total population of the region at the end of the year. Financial human resources are measured by the number of financial practitioners at the end of the year as a percentage of the total population of the region. Higher education resources are measured by the number of college students per 10,000 population.

Financial support for science and technology includes: Financial support is primarily measured by the ratio of financial science and technology spending to total financial spending. R&D spending is measured as a percentage of GDP.

Financing of science and technology finance includes: Financial depth is mainly measured by the proportion of the loan balances of financial institutions in the regional GDP. Credit capacity is measured by the ratio of the balance of deposits held by financial institutions to GDP. The number of regional listings measures the state of the listed companies. Insurance depth is measured as the proportion of insurance revenues in GDP.

Scientific and technological financial output includes: Patent yield rate is measured as the ratio of the number of patents granted to the amount spent on scientific research. Patent intensity is mainly measured by the ratio of patent ownership to the labour force.

3.1.2 Indicator system of green development

Under the background of ecological civilization construction, economic growth transformation and social governance modernization, this paper constructs a more comprehensive and systematic green development measurement index with the general direction of "efficiency, harmony and sustainability". Meanwhile, according to the contents of the Assessment Target System for Ecological Civilization Construction and the Green Development Indicator System, and referring to the research of Huang and Wu (2019) and Hu et al. (2021), from four aspects of ecological construction, economic development, social welfare and system supply, this paper selects 40 relevant indicators to build a comprehensive indicator system for green development (see Table 1).

3.1.3 Determination of index weight by entropy method

Based on the above indicators of science and technology finance and green development, as well as their data characteristics, this paper uses entropy method to calculate the comprehensive indicators of science and technology finance and green development. The entropy method determines the weight according to the dispersion degree of the index, which is an objective method of giving weight, avoiding the interference of subjective factors, to ensure the accuracy and reliability of the index information entropy (Bai et al., 2020). The greater the degree of dispersion, the more information, the greater the weight, but the smaller the entropy. The original data of indicators can be expressed in $m \times n$ matrix form. M represents the number of samples, and n represents the number of indicators.

$$X = \begin{bmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mn} \end{bmatrix} \quad (1)$$

1) To avoid the impact of different dimensions of indicators on the evaluation results, this paper conducts dimensionless processing of indicators. For positive indicators, the normalized value can be measured by the following formula:

$$x'_{ij} = \frac{x_{ij} - minx_{ij}}{maxx_{ij} - minx_{ij}} \quad (2)$$

For negative indicators, the normalized value can be calculated with the following formula:

$$x'_{ij} = \frac{max\, x_{ij} - x_{ij}}{maxx_{ij} - minx_{ij}} \quad (3)$$

Where x_{ij} represents the value of the j th evaluation index of sample i ($i = 1, 2, 3, \ldots, m$; $j = 1, 2, 3, \ldots, n$).

2) Calculate the proportion of index j in the i th sample value:

$$P_{ij} = \frac{x'_{ij}}{\sum_{i=1}^{m} x'_{ij}} \quad (4)$$

3) Calculate the entropy value e of the j th index e_j:

$$e_j = -\frac{1}{lnn} \sum_{i-1}^{m} P_{ij} lnP_{ij} \quad (5)$$

4) Calculate the weight w of the j th index w_j:

$$w_j = \frac{1 - e_j}{\sum_{j=1}^{n} \left(1 - e_j\right)} \quad (6)$$

5) Calculate the comprehensive score of indicators:

$$Z = \sum_{j=1}^{n} x'_{ij} w_j \quad (7)$$

3.1.4 Science and technology finance and green development in China

In this paper, we adopt the entropy method introduced above to build an indicator system for the financial and green development of China's urban science and technology sector. We calculate the average composite index of these two indicators from 2003 to 2020. In order to more intuitively see the changing trend of science and technology finance and green development over time, this paper has drawn a line chart of the average composite index of science and technology finance and green development from 2003 to 2020 (Figure 2). Overall, the average composite index of science and technology finance and green development shows an upward trend.

TABLE 1 Green development indicator evaluation system.

Level 1 indicator	Level 2 indicator	Level 3 indicator	Attribute
Ecological construction	Resource endowment	Green area *per capita*	+
		Afforestation area	+
		Total water supply	+
	Energy consumption	Per capita water consumption	-
		Power consumption *per capita*	-
		Industrial power consumption	-
	Pollutant discharge	Industrial wastewater discharge	-
		Emission of industrial sulfur dioxide	-
		Industrial smoke and dust emission	-
		Industrial nitrogen oxide emissions	-
Economic development	Industrial structure	Ratio of secondary industry to GDP	-
		Ratio of tertiary industry to GDP	+
		Number of employees in the secondary industry	-
		Number of employees in the tertiary industry	+
		Actual utilized foreign capital	+
	Economic growth	GDP *per capita*	+
		GDP growth rate	+
		Resident savings balance	+
		Total retail sales of consumer goods	+
		Average wages of on duty employees	+
		Total profit of industrial enterprises	+
Social welfare	Social security	Natural population growth rate	-
		Number of urban registered unemployed	-
		Number of health and social welfare employees	+
		Number of employees in education industry	+
		Amount of social welfare relief	+
	Green life	Population density	-
		Per capita urban road area	+
		Green coverage rate of built-up area	+
		Bus ownership per 10,000 people	+
Institutional supply	Infrastructure	Length of drainage pipe	+
		Public library collection per 100 people	+
		Number of beds in medical and health institutions	+
		Investment in urban environmental infrastructure	+
	Environmental governance	Investment in pollution source control	+
		Output value of three wastes comprehensive utilization products	+
		Sewage treatment rate	+
		Domestic garbage harmless treatment rate	+

(Continued on following page)

TABLE 1 (*Continued*) Green development indicator evaluation system.

Level 1 indicator	Level 2 indicator	Level 3 indicator	Attribute
		Removal rate of industrial sulfur dioxide	+
		Industrial dust removal rate	+

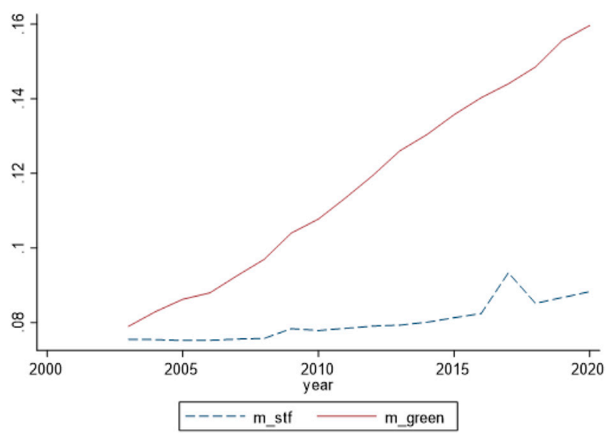

FIGURE 2
Broken line chart of average comprehensive index of science and technology finance and green development from 2003 to 2020.

However, the science and technology finance index peaked in 2017 and recovered from a stable upward trend. According to the records of major events in science and technology finance, the Chinese government paid enough attention to the development of science and technology finance in 2017 and wrote "science and technology finance ecology" into the 13th Five-Year National Science and Technology Innovation Plan for the first time. The concept of science and technology finance ecology was also widely accepted. In addition, the trend of the average composite index for green development is relatively steep, as seen from the figure. In contrast, the trend of the average composite index of science and technology finance is relatively flat, indicating that the green development of Chinese cities has achieved more notable results. As a developing country, China's integration of science, technology and finance has achieved phased results, but it is still in its infancy. The development of science and technology finance still faces enormous risks and challenges.

3.2 Coupling coordination degree model

The coupling degree is originally a concept in the computer field, which is a measure of the degree of correlation between modules. In this paper, the interaction between the science and technology finance subsystem and the green development subsystem is understood as the degree of coupling between the two. In order to quantitatively analyze the coupling level of the compound system of science and technology finance and green development, we have established a coupling degree model that can reflect the interaction between the subsystems of science and technology finance and green development.

However, the degree of coupling can only represent the degree of interaction between the systems in the time dimension (Pan and Dong, 2023). In contrast, for multi-area comparisons in spatial dimensions, the method of computing the coupling degree may lead to spurious evaluation results. The coupling degree can judge the degree of coordination between the two systems (Tao et al., 2023). However, if each system has a relatively low level of development, a high coupling degree may still be obtained, which is contrary to the actual situation (Xu et al., 2023). Because the subsystems of science and technology finance and green development are interlaced, unbalanced and dynamic, this paper can not accurately reflect their interaction's synergy and overall effectiveness by only using the coupling degree. Therefore, to further analyze the degree of coordination of the composite system, in this paper, we introduce the coupled degree of coordination model, which is calculated as follows:

$$D = \sqrt{C \times T} \tag{8}$$

$$C = \frac{2 \times \sqrt{U_{stf} \times U_{green}}}{U_{stf} + U_{green}} \tag{9}$$

$$T = \alpha \times U_{stf} + \beta \times U_{green} \tag{10}$$

TABLE 2 Classification of coupling coordination types.

D	Coupling stage	Characteristic
$0 < D \le 0.3$	Low coupling coordination	The coupling relationship between science and technology finance and green development is not obvious, and the coupling system is less orderly
$0.3 < D \le 0.5$	Moderate coupling coordination	The coupling mechanism between science and technology finance and green development has gradually taken shape, and they are in a state of mutual restriction
$0.5 < D \le 0.8$	High coupling coordination	The coupling degree between science and technology finance and green development is high, and the coupling coordination is constantly strengthened
$0.8 < D \le 1.0$	Extreme coupling coordination	The coupling degree and coordination between science and technology finance and green development has reached a very high level, and the coupling system is in an orderly state

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TABLE 3 Unit root test.

Test	Science and technology finance		Green development		Coupling coordination degree	
	I (0)	I (1)	I (0)	I (1)	I (0)	I (1)
LLC	−1.17	−41.73***	3.22	−26.35***	−2.89***	−36.54***
IPS	−11.28***	−41.94***	11.12	−33.278***	−9.73***	−40.84***
HT	0.313***	−0.50***	0.99	−0.185***	0.54***	−0.49***
ADF	642.20***	3942.30***	383.32	2365.21***	693.32***	3300.59***

Note: * * *, * *, * respectively represent significant at 1%, 5%, and 10% significance levels.

Where D represents the coupling coordination index; C is the coupling degree; T is the comprehensive coordination index of science and technology finance and green development; U_{stf} represents the comprehensive evaluation index of science and technology finance; U_{green} represents the comprehensive evaluation index of green development; α and β are undetermined coefficients. This paper holds that science and technology finance and green development are equally important, and refers to Guo et al. (2021), making $\alpha = \beta = 0.5$. The range of coupling coordination degree D is (0, 1]. According to Zhang et al. (2013)'s criteria for the division of coupling coordination relations, the coupling coordination degree is divided into four intervals, as shown in Table 2.

3.3 Preliminary preparation of PVAR model

3.3.1 Model setting

We believe that this work also contributed to the achievement of sustainable development goals (SDGs) and ecological civilization, which are important directions for China (Bryan et al., 2018; Sun et al., 2018; Jiang et al., 2022). In order to study the interaction between science and technology finance, green development and their coupling and coordination levels, this paper constructs a panel vector autoregression model (PVAR) for analysis. The PVAR model does not need to set the causal relationship between variables and distinguish between endogenous and exogenous variables in advance but regards all variables as endogenous variables and then analyzes the interaction between each variable and the lagging term (Feng and Yang, 2023; Sharif et al., 2023). The model is set in the following formula.

$$Y_{it} = \alpha_0 + \sum_{j=1}^{k} \alpha_j Y_{i,t-j} + \beta_i + \gamma_t + \varepsilon_{it} \tag{11}$$

Where i and t represent city and year respectively; Y_{it} is a column vector containing science and technology finance, green development and their coupling coordination level; α_j is the coefficient matrix of the lagging variable; β_i represents the city effect column vector, conveying the individual differences of prefecture level cities; γ_t represents the dummy variable of time effect, reflecting the impact of time change on different cities; ε_{it} is the random disturbance term.

3.3.2 Stationarity test

In order to ensure the accuracy of the model estimation and avoid the "spurious regression" phenomenon, this paper first tests the stationarity of the three variables of science and technology finance, green development, and their coupling coordination level before estimating the model. Common unit root test methods for panel data include the following four methods: LLC test, IPS test, HT test, and ADF test. The above unit root test methods have different conditions to apply, but the initial assumption is that all variables have unit roots; the data is unstable. Assume that the result of the original data is not stable. In that case, it is necessary to perform first-order difference processing on the data and then re-perform the unit root test on the differential sequence until the result is stable. In order to ensure the stability of the results, in this paper, we will check the existence of a root of unity in the variables simultaneously using the above four methods. See Table 3 for the

TABLE 4 Selection of optimal lag order of PVAR model.

Lag order	AIC	BIC	HQIC
1	−19.503*	−18.225*	−19.050*
2	−19.273	−17.904	−18.786
3	−18.327	−16.855	−17.802
4	−14.351	−12.760	−13.782
5	−16.431	−14.702	−15.809

Note: * represents the optimal lag order selected according to AIC, BIC, and HQIC, criteria.

test results. It can be found that science and technology finance and green development cannot be significant at the level of 5%, indicating that these two variables are unstable. All variables after the first order difference pass the 1% significance level test, indicating that the data obtained after the first order difference is stable for science and technology finance, green development and their coupling coordination level.

In order to verify whether there is a long-term stable equilibrium relationship between science and technology finance, green development and their coupling coordination levels, we employ the Kao test method to carry out a cointegration test on the data after the first-order difference of all variables. Kao test results show that the t-statistic value of ADF is -13.4828, and the p-value is 0.0000, which means that the original hypothesis is rejected, indicating a stable equilibrium relationship between science and technology finance, green development and their coupling coordination levels.

3.3.3 Selection of optimal lag order of PVAR model

Before PVAR model regression, it is necessary to determine the optimal lag order of the model. This paper refers to Yang (2017)'s practice and determines the optimal lag order according to the minimum values of AIC, BIC and HQIC. The results are shown in Table 4. It can be found that the optimal lag order of AIC, BIC and HQIC is order 1. Therefore, the lag order of the PVAR model is set as order one in this paper.

4 Results and discussion

4.1 Time analysis of the systematic coupling between science and technology finance and green development

4.1.1 Overall time characteristics

Based on the coupling coordination model, this paper uses panel data of 274 cities in China from 2003 to 2020 to calculate the coupling coordination of science and technology finance and green development. In Table 5, U_{stf} represents the development level of science and technology finance, and U_{green} is the green

TABLE 5 The overall characteristics of the coupling and coordination relationship between science and technology finance and green development.

Year	Ustf	Ugreen	Ustf/Ugreen	Cstf_green	Dstf_green	Coupling coordination type
2003	0.0755	0.0790	0.9559	0.9534	0.2698	Low coupling coordination
2004	0.0754	0.0829	0.9093	0.9527	0.2729	Low coupling coordination
2005	0.0752	0.0862	0.8719	0.9509	0.2752	Low coupling coordination
2006	0.0752	0.0880	0.8555	0.9500	0.2765	Low coupling coordination
2007	0.0756	0.0926	0.8165	0.9484	0.2805	Low coupling coordination
2008	0.0757	0.0970	0.7812	0.9460	0.2838	Low coupling coordination
2009	0.0784	0.1040	0.7534	0.9419	0.2896	Low coupling coordination
2010	0.0779	0.1077	0.7227	0.9446	0.2935	Low coupling coordination
2011	0.0784	0.1134	0.6915	0.9412	0.2977	Low coupling coordination
2012	0.0790	0.1194	0.6619	0.9386	0.3020	Moderate coupling coordination
2013	0.0793	0.1260	0.6292	0.9349	0.3061	Moderate coupling coordination
2014	0.0801	0.1304	0.6141	0.9332	0.3096	Moderate coupling coordination
2015	0.0813	0.1357	0.5988	0.9321	0.3139	Moderate coupling coordination
2016	0.0824	0.1403	0.5875	0.9310	0.3178	Moderate coupling coordination
2017	0.0934	0.1440	0.6482	0.9674	0.3343	Moderate coupling coordination
2018	0.0852	0.1486	0.5732	0.9320	0.3253	Moderate coupling coordination
2019	0.0867	0.1557	0.5568	0.9305	0.3304	Moderate coupling coordination
2020	0.0883	0.1597	0.5530	0.9297	0.3337	Moderate coupling coordination

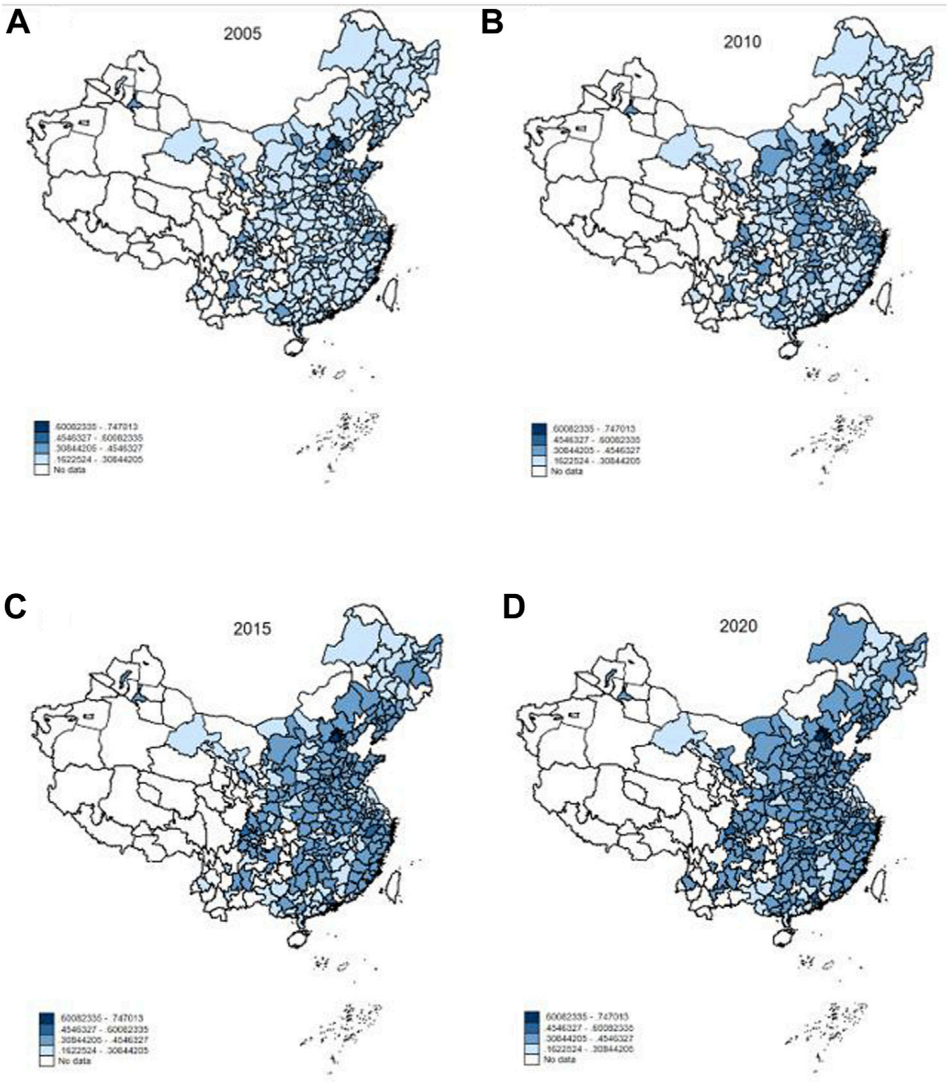

FIGURE 3
The spatial pattern evolution of the coupling coordination degree between the scientific and technological finance system and the green development system. **(A)** The coupling and coordination of science and technology finance and green development in 2005; **(B)** The coupling and coordination of science and technology finance and green development in 2010; **(C)** The coupling and coordination of science and technology finance and green development in 2015; **(D)** The coupling and coordination of science and technology finance and green development in 2020.

development level. U_{stf}/U_{green} represents the ratio of science and technology finance to green development, which is used to measure the leading or lagging degree of science and technology finance relative to green development. If the ratio is less than 1, it indicates that the science and technology finance system lags behind the green development system; If the ratio is greater than 1, it means that science and technology finance is ahead of the green development system; If the ratio is equal to 1, it means that technology finance and green development are developing simultaneously. C_{stf_green} refers to the coupling degree between science and technology finance system and green development, which is used to measure the correlation degree between science and technology finance and green development. D_{stf_green} indicates the coupling and coordination between science and technology finance and green development. The higher the value, the higher the coupling and coordination level between them.

Table 5 shows that science and technology finance and green development have relatively high coupling. The average coupling degree is 0.9421 through calculation, conveying that science and technology finance and green development have a high correlation, and the correlation is decreasing year by year. However, the relationship between science and technology finance and green development was low coupling and coordination before 2011. In 2011 and later, their relationship changed from low coupling and coordination to medium coupling and coordination. Throughout the sample period, the degree of coupling and coordination between science and technology finance and green development is rising yearly, which shows that the mutual support and promotion between the two have been strengthened. At the same time, it

TABLE 6 The coupling coordination of science and technology finance and green development in China's seven urban agglomerations.

Year	Beijing-Tianjin-Hebei	Yangtze River Delta	Pearl River Delta	Chengdu-Chongqing	Middle Yangtze River	Guanzhong Plain	Central Plains
2003	0.3108	0.2693	0.2644	0.2799	0.2625	0.2573	0.2852
2004	0.3184	0.2759	0.2682	0.2823	0.2666	0.2611	0.2877
2005	0.3201	0.2799	0.2715	0.2855	0.2671	0.2629	0.2889
2006	0.3207	0.2834	0.2735	0.2874	0.2683	0.2653	0.2894
2007	0.3269	0.2888	0.2814	0.2890	0.2716	0.2685	0.2960
2008	0.3330	0.2929	0.2863	0.2932	0.2744	0.2735	0.2997
2009	0.3406	0.3010	0.2969	0.2947	0.2854	0.2797	0.3031
2010	0.3474	0.3058	0.3090	0.3001	0.2829	0.2813	0.3069
2011	0.3509	0.3137	0.3164	0.3061	0.2854	0.2831	0.3101
2012	0.3569	0.3195	0.3228	0.3131	0.2904	0.2878	0.3133
2013	0.3603	0.3250	0.3352	0.3196	0.2939	0.2906	0.3165
2014	0.3657	0.3291	0.3338	0.3230	0.2974	0.2957	0.3211
2015	0.3715	0.3353	0.3406	0.3286	0.3009	0.2978	0.3246
2016	0.3772	0.3413	0.3490	0.3315	0.3056	0.3011	0.3279
2017	0.3817	0.3735	0.3941	0.3346	0.3292	0.3226	0.3300
2018	0.3852	0.3536	0.3791	0.3385	0.3146	0.3068	0.3326
2019	0.3893	0.3615	0.3771	0.3509	0.3170	0.3135	0.3366
2020	0.3950	0.3717	0.3865	0.3475	0.3217	0.3148	0.3395
Average	0.3529	0.3178	0.3214	0.3114	0.2908	0.2869	0.3116
N	234	468	144	288	504	198	522

can also be found that the science and technology finance system continues to lag behind the green development system. The gap between the two systems gradually increases over time, which may be why the coupling and coordination level of science and technology finance and green development cannot be further improved (Yin et al., 2022). Therefore, this conclusion implies that improving the development level of science and technology finance is the key to optimizing the high coupling and coordination between science and technology finance and green development.

In order to more intuitively analyze the dynamic evolution and spatial pattern of the coupling and coordination degree of science and technology finance and green development in cities across the country, this paper takes 2015 and 2020 as time nodes to visualize the coupling and coordinated development of science and technology finance and green development in 274 cities in China, as shown in Figure 3. It can be seen that in these four periods, the coupling and coordination degree of science and technology finance and green development system showed a gradient change trend in space, that is, from inland areas to coastal areas. The coupling and coordination degree of eastern cities with the more developed economy is generally higher than that of central and western cities with lower economic development and northeast cities. In addition, in 2005, the coupling coordination degree of most cities in China was mainly concentrated in the range of 0.1622524–0.30844205. By 2020, most cities' coupling and coordination degree will rise to 0.4546327–0.60082335, which indicates that the coupling and coordination degree between science and technology finance and green development will increase significantly over time (Yin and Xu, 2022).

4.1.2 Characteristics of seven urban agglomerations

Table 6 shows the basic characteristics of the coupling and coordination degree between science and technology finance and green development of China's seven urban agglomerations from 2003 to 2020. The Beijing-Tianjin-Hebei, Yangtze River Delta and Pearl River Delta regions have a high level of coordination between science and technology finance and green development, which belongs to the first ladder level at the level of urban agglomeration. Among them, the coupling coordination degree of the Beijing-Tianjin-Hebei region has increased from 0.3108 in 2003 to 0.3950 in 2020, which is in a moderate coupling coordination within the observation period. The coupling coordination degree of the Yangtze River Delta and the Pearl River Delta increased from 0.2693 to 0.2644 in 2003 to 0.3717 and 0.3865 in 2020, respectively, from low coupling coordination to medium coupling coordination. The turning points were in 2009 and 2010, respectively.

TABLE 7 Descriptive statistics of comprehensive scores of science and technology finance and green development in China's seven urban agglomerations.

Region	Science and technology finance				Green development			
	Mean	Std	Min	Max	Mean	Std	Min	Max
Beijing-Tianjin-Hebei	0.104	0.046	0.083	0.391	0.169	0.126	0.062	0.796
Yangtze River Delta	0.084	0.050	0.014	0.353	0.151	0.091	0.051	0.784
Pearl River Delta	0.078	0.055	0.014	0.303	0.174	0.098	0.075	0.521
Chengdu- Chongqing	0.087	0.022	0.013	0.158	0.124	0.089	0.051	0.549
Middle Yangtze River	0.074	0.037	0.012	0.605	0.112	0.041	0.051	0.352
Guanzhong Plain	0.076	0.030	0.013	0.140	0.103	0.044	0.043	0.321
Central Plains	0.087	0.004	0.082	0.115	0.112	0.034	0.055	0.309

The level of coupling and coordination between science, technology, finance and green development in Chengdu-Chongqing and Central Plains is relatively close, belonging to the second ladder level at the level of urban agglomeration. The coupling and coordination degree of the two increased from 0.2799 to 0.2852 in 2003 to 0.3475 and 0.3395, respectively, from low coupling and coordination to medium coupling and coordination. The turning point occurred in 2010 and 2009, respectively.

The coupling coordination level of the middle reaches of the Yangtze River, and the Guanzhong Plain is relatively low, belonging to the third ladder level at the level of urban agglomeration. The coupling coordination degree of the two areas has risen from 0.2625 to 0.2573 in 2003 to 0.3217 and 0.3148 in 2020, respectively, from low coupling coordination to medium coupling coordination. The turning points occurred in 2015 and 2016, respectively.

From the average value of the coupling coordination of each urban agglomeration, it is found that the average coupling coordination level of the seven urban agglomerations is ranked in the order of large to small: Beijing-Tianjin-Hebei > Pearl River Delta > Yangtze River Delta > Central Plains > Chengdu-Chongqing > Yangtze River Delta > Guanzhong Plain.

In order to further analyze the reasons for the imbalance of the coupling and coordination between science and technology finance and green development among urban agglomerations, this paper makes descriptive statistics on the comprehensive scores of science and technology finance and green development of the seven urban agglomerations in the observation period, as shown in Table 7. It can be found that the regional difference between science and technology finance is lower than that of green development. The maximum value of the average comprehensive score of science and technology finance is 0.104, and the minimum value is 0.074; that is, the maximum value is 1.41 times the minimum value. The maximum average comprehensive score of green development is 0.174, and the minimum is 0.103; that is, the maximum is 1.69 times the minimum. The considerable difference in green development among urban agglomerations may be the key reason for the imbalance of coupling and coordination between science and technology finance and green development, which is similar to the explanation of Hou et al. (2022). The average comprehensive scores of science and technology finance and green development in Guanzhong Plain urban agglomeration are low, which leads to the lowest coupling coordination between science and technology finance and green development. The Beijing-Tianjin-Hebei urban agglomeration is the only region where the average comprehensive science and technology finance score is greater than 0.1. The enormous advantages of science and technology finance make the Beijing-Tianjin-Hebei urban agglomeration's average coupling coordination degree rank first among the seven urban agglomerations.

4.2 Spatial analysis of the systematic coupling between science and technology finance and green development

Based on the nested matrix of spatial economic geography, this paper verifies the spatial relevance of the coupling and coordination relationship between science and technology finance and green development by calculating Moran's I index.

4.2.1 Overall spatial effect

Table 8 reports the overall Moran index of the coupling and coordination of science, technology, finance, and green development in 274 cities in China. During the observation period, the Moran index of coupling coordination degree was positive. However, it did not pass the 10% significance level test between 2003 and 2005, indicating no spatial autocorrelation between the coupling coordination level of early science and technology finance and green development. Since 2006, the Moran index of coupling coordination degree has begun to be significant, and the significance level is also gradually increasing. In 2010 and later, the Moran index passed the significance level of 1%. Therefore, we believe that the coordinated and interactive relationship between science and technology finance and green development positively correlates in space. At the same time, from the perspective of the evolution trend, the Moran index of the coupling and coordination degree shows an overall upward trend of fluctuation, indicating the spatial correlation between the coupling and coordination of science

TABLE 8 Global Moran index of the coupling and coordination degree of science and technology finance and green development.

Year	Moran's I	Year	Moran's I	Year	Moran's I
2003	0.035	2009	0.077**	2015	0.125***
	(1.179)		(2.476)		(3.973)
2004	0.041	2010	0.092***	2016	0.139***
	(1.380)		(2.935)		(4.415)
2005	0.046	2011	0.104***	2017	0.223***
	(1.521)		(3.315)		(7.079)
2006	0.059*	2012	0.109***	2018	0.191***
	(1.928)		(3.469)		(6.026)
2007	0.065**	2013	0.122***	2019	0.168***
	(2.115)		(3.864)		(5.310)
2008	0.071**	2014	0.117***	2020	0.190***
	(2.279)		(3.710)		(6.001)

Note: * * *, * *, * respectively represent significant at 1%, 5%, and 10% significance levels; The values in parentheses are the corresponding z-statistics.

and technology finance and green development is growing. Guo et al. (2021) confirmed this conclusion.

4.2.2 Spatial effect of seven urban agglomerations

Furthermore, this paper calculates the Moran index of the coupling and coordination degree of science, technology, finance, and green development of China's seven urban agglomerations. The results are shown in Table 9. Overall, only the Beijing-Tianjin-Hebei urban agglomeration and the Yangtze River Delta urban agglomeration have significantly positive Moran exponents for coupling coordination. The Moran index of the Pearl River Delta urban agglomeration did not pass the 10% significance level test in 2018 and was significant in other years. From the value of the coefficient, the Moran index of the Yangtze River Delta urban agglomeration is increasing yearly, indicating the spatial relevance of the coupling and coordination relationship between science, technology and finance and green development in the region continues to increase. The Moran index of the Beijing-Tianjin-Hebei urban agglomeration rose slowly until 2012 but declined thereafter. The Moran index of the Pearl River Delta urban agglomeration is mainly volatile. The Moran index of Chengdu-Chongqing, the middle reaches of the Yangtze River, the Guanzhong Plain, the Central Plains, and other urban agglomerations is positive or negative. However, they have not passed the significance test, indicating no spatial correlation between the coupling and coordination of science and technology finance and green development in such urban agglomerations. To sum up, the imbalance and disharmony between science and technology finance and green development in various regions of China still exist (Tian and Wang, 2022). The development process of the coupling and coordination of science and technology finance and green development is relatively long. In the future, cities need to cooperate, improve the circulation of innovation elements, build a joint governance mechanism for the ecological environment, and jointly promote high-quality regional development (Han et al., 2021).

Based on the above analysis of the Moran index of the coupling and coordination of the seven urban agglomerations, the spatial correlation of the coupling and coordination of science and technology finance and green development needs to attach importance to the development of its subsystems (Fan et al., 2019). The development of the subsystem not only refers to the development of the green economic system but also includes the development of the scientific and technological financial system. Coupling coordination's spatial relevance can be reflected when the level of science and technology finance and green development systems is high. When both systems' development level is low, the coupling system will fall into a "low-end equilibrium" (Lai et al., 2020). Meanwhile, combining the above analysis of the temporal properties of the coupling and coordination of the seven urban agglomerations, it can be seen that the spatial radiation effect is strong when the level of coupling and coordination between the systems is in the high-coupling regime. When the level of coupling and coordination between the two systems is low, the spatial radiation effect is also weakened (Ge et al., 2022).

4.3 The interaction between science and technology finance, green development and their coupling coordination

4.3.1 Analysis of PVAR model results

This paper estimates the GMM of the PVAR model for 274 cities, analyzes the long-term interaction between science and technology finance, green development and their coupling coordination levels, and the results are shown in Table 10. It can be seen that there is a significant positive correlation between science and technology finance lagging by one period and its current level,

TABLE 9 The spatial relevance of the coupling coordination degree of science and technology finance and green development in China's seven urban agglomerations.

year	Beijing-Tianjin-Hebei	Yangtze River Delta	Pearl River Delta	Chengdu- Chongqing	Middle Yangtze river	Guanzhong Plain	Central Plains
2004	0.171**	0.295***	0.182*	0.039	0.016	−0.012	0.087
	(2.256)	(3.078)	(1.848)	(0.629)	(0.447)	(0.518)	(1.080)
2006	0.200**	0.316***	0.162*	0.005	−0.003	−0.032	−0.036
	(2.240)	(3.290)	(1.739)	(0.430)	(0.289)	(0.392)	(-0.006)
2008	0.200**	0.333***	0.185*	0.002	0.020	−0.084	−0.053
	(2.432)	(3.464)	(1.898)	(0.405)	(0.478)	(0.094)	(-0.159)
2010	0.200***	0.384***	0.180*	0.021	0.015	−0.084	−0.036
	(2.582)	(3.970)	(1.915)	(0.507)	(0.441)	(0.092)	(-0.005)
2012	0.204***	0.409***	0.172*	0.075	−0.005	−0.079	−0.033
	(2.589)	(4.253)	(1.872)	(0.821)	(0.276)	(0.127)	(0.031)
2014	0.190**	0.423***	0.170*	0.063	−0.003	−0.109	−0.007
	(2.550)	(4.457)	(1.862)	(0.750)	(0.290)	(-0.052)	(0.274)
2016	0.191***	0.458***	0.180*	0.079	0.008	−0.069	−0.018
	(2.624)	(4.753)	(1.926)	(0.832)	(0.383)	(0.187)	(0.183)
2018	0.174***	0.478***	0.059	0.088	0.064	−0.065	−0.032
	(2.595)	(4.912)	(1.272)	(0.884)	(0.860)	(0.214)	(0.035)
2020	0.160**	0.495***	0.153*	0.070	−0.009	−0.061	−0.029
	(2.528)	(5.137)	(1.787)	(0.784)	(0.238)	(0.248)	(0.074)

Note: * * *, * *, * respectively represent significant at 1%, 5%, and 10% significance levels; The values in parentheses are the corresponding z-statistics.

TABLE 10 GMM estimation results of PVAR model.

Variables	h_Dstf	h_Dgreen	h_Dcoupl
L.h_Dstf	0.214***	0.015**	0.270***
	(3.37)	(2.13)	(12.52)
L.h_Dgreen	0.378***	−0.152***	0.377***
	(8.16)	(-2.73)	(8.14)
L.h_Dcoupl	−0.524***	−0.040***	−0.671***
	(−11.15)	(−4.35)	(−21.78)

Note: * * *, * *, * respectively represent significant at 1%, 5%, and 10% significance levels; The data in brackets are standard deviation.

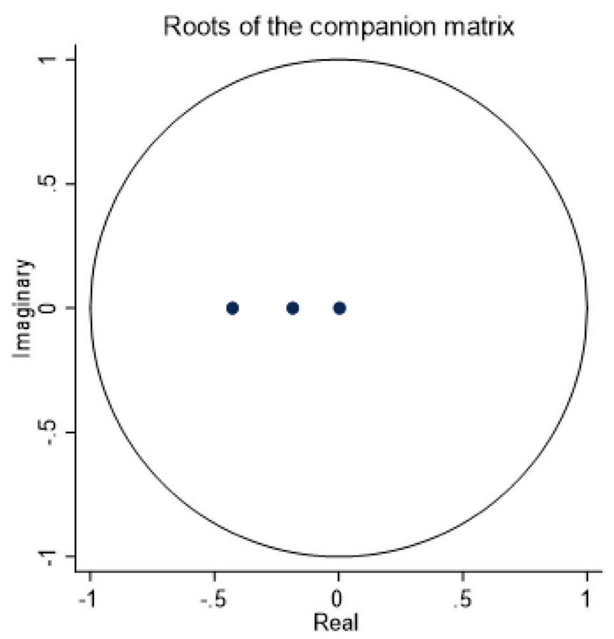

FIGURE 4
Stability test.

and the estimated coefficient is 0.214, representing that science and technology finance has a self-promoting effect.

At the same time, it is found that the estimated coefficients of the current green development level and coupling coordination level of science and technology finance lagging by one period are 0.015 and 0.270, respectively. Both pass the 5% significance level test, indicating that science and technology finance can significantly improve urban green development and the coordinated development level between the two. The green development lagging by one period significantly negatively affects its current level. The estimated coefficient is −0.152, indicating that the green development level has a self-inhibition effect. One possible reason is that the four dimensions of green development, namely ecological construction, economic development, social welfare, and institutional supply, are still unbalanced. The estimation coefficient of green development lags by one period to the current science and technology finance level. The level of coupling and coordination is significantly positive, indicating that green development is at a higher level, requiring a higher level of science and technology finance development to serve it (Ibrahim et al., 2022). It is more conducive to coordination and progress between the two.

In addition, the coefficient of the coupling coordination lagging behind Phase 1 to the current coupling coordination level, science and technology finance and green development is significantly negative, indicating that the higher coordinated development of science and technology finance and green development in the early stage is not conducive to their respective development in the current period and the coupling coordination level between them. The possible reason is that the level of coordinated development between science and technology finance and green development is relatively high, which will restrict their development (Wang and Wang, 2021). It can be seen from the estimation coefficient of the regression of the coupling coordination level lagging behind the first period to the current science and technology finance and green development that the impact of the coupling coordination level on their development is quite different, which will also aggravate the imbalance between science and technology finance and green development.

Before equation decomposition analysis, it is necessary to ensure the stability of the PVAR model system (Apostolakis and Papadopoulos, 2019). First, calculate the unit root eigenvalue of the model and then check whether all the eigenvalues fall within the unit circle to judge the stability of the PVAR model system. The results are displayed in Figure 4. It can be seen that the three estimation points all fall within the unit circle; that is, the mean values of the three characteristic values are less than 1, implying that the impact of one variable on the other variable will gradually weaken until it disappears. The model system tends to be stable. Therefore, the PVAR model built in this paper is stable.

4.3.2 Variance decomposition

Variance decomposition is mainly used to measure the contribution of different random error terms to the fluctuation of endogenous variables. It can accurately reflect the degree of interaction between various variables (Huang et al., 2009). Therefore, to further measure the relationship between science and technology finance, green development, and their coupling and co-scheduling, this paper conducts variance decomposition for the prediction errors of all variables. The variance decomposition results can be calculated simultaneously during the impulse response function analysis. The number of periods is set as 10, and the results are reported in Table 11.

10.3389/fenvs.2023.1090998

TABLE 11 Variance decomposition result.

Response variables	Periods	Shock variable		
		Dstf	Dgreen	Dcoupl
Dstf	1	0.3540	0.0391	0.6069
Dstf	2	0.3356	0.0470	0.6174
Dstf	3	0.3325	0.0487	0.6188
Dstf	4	0.3319	0.0491	0.6190
Dstf	5	0.3318	0.0492	0.6191
Dstf	6	0.3317	0.0492	0.6191
Dstf	7	0.3317	0.0492	0.6191
Dstf	8	0.3317	0.0492	0.6191
Dstf	9	0.3317	0.0492	0.6191
Dstf	10	0.3317	0.0492	0.6191
Dgreen	1	0	0.9540	0.0460
Dgreen	2	0.0005	0.9470	0.0523
Dgreen	3	0.0006	0.9455	0.0539
Dgreen	4	0.0007	0.9452	0.0541
Dgreen	5	0.0007	0.9452	0.0541
Dgreen	6	0.0007	0.9452	0.0541
Dgreen	7	0.0007	0.9452	0.0541
Dgreen	8	0.0007	0.9451	0.0542
Dgreen	9	0.0007	0.9451	0.0542
Dgreen	10	0.0007	0.9451	0.0542
Dcoupl	1	0	0	1
Dcoupl	2	0.0265	0.0105	0.9630
Dcoupl	3	0.0305	0.0140	0.9556
Dcoupl	4	0.0312	0.0148	0.9540
Dcoupl	5	0.0313	0.0150	0.9537
Dcoupl	6	0.0314	0.0150	0.9537
Dcoupl	7	0.0314	0.0150	0.9536
Dcoupl	8	0.0314	0.0150	0.9536
Dcoupl	9	0.0314	0.0150	0.9536
Dcoupl	10	0.0314	0.0150	0.9536

Science and technology finance is affected by three aspects. Among them, the impact of the coupling coordination level is the main one. The impact of the first phase is 60.69% from the coupling coordination level, increasing gradually to 61.91% in the fifth phase. The self-development of science and technology finance is the second long-term influencing factor. The self-contribution of the first period is 35.4%, and the second period has weak growth, but then it decreases gradually until the sixth period is 33.17% and tends to be stable. The impact of green development is relatively small, 3.91% in the first phase, and then gradually increases to the fifth phase and tends to be stable.

Green development is mainly affected by the following two aspects: its development and the improvement of the level of coupling and coordination. The contribution of green development began to appear in the first phase and reached the maximum value, and then gradually decreased from 95.40% to 94.51% and became stable. The influence of the improvement of the coupling coordination level also appeared in the first phase and increased gradually until the eighth phase became stable, from 4.6% to 5.42%. The impact of science and technology finance is relatively small. It began contributing to green development in Phase 2 and was stable at 0.07% in Phase 4.

The coupling and coordination degree improved due to its contribution in the first phase. Since the second phase, the impact of science and technology finance and green development has gradually emerged. The impact of science and technology finance is more prominent. The influence of coupling coordination degree decreases gradually from the first phase to the seventh phase and tends to be stable. The contribution of science and technology finance and green development increased gradually from the second phase. The contribution rate of science and technology finance reached the maximum and stabilized in the sixth phase. The impact of green development on the coupling coordination degree reaches the maximum and tends to be stable when it reaches the fifth stage, with a contribution rate of 1.5%.

From the above analysis of the equation decomposition of science and technology finance, green development, and their coupling coordination degree, it can be seen that these three have mutual influence in the long run. Although science and technology finance plays a relatively minor role in improving urban green development, it is still an essential factor that cannot be ignored. The interaction between science and technology finance and the level of coupling and coordination is relatively large. Therefore, when pursuing the coordinated development of science and technology finance and green development, we should pay more attention to the development of science and technology finance (Lv et al., 2021).

5 Conclusion and policy recommendations

This paper uses the coupling coordination model to study the interaction between science and technology finance and green development and evaluate their coordinated development level. Then we adopt the PVAR model and impulse response function to examine the dynamic causal relationship between science and technology finance and green development. The research shows that.

1) The coupling coordination model calculates the coupling degree and coordination of China's urban science and technology finance and green development. The average coupling degree results show a high correlation between them. However, the type of coupling coordination rises from low to medium in the sample period.
2) The Beijing-Tianjin-Hebei, Yangtze River Delta, and Pearl River Delta have a high level of coupling and coordination, which is at the first ladder level. Chengdu-Chongqing and the Central Plains

belong to the second step, while the middle reaches of the Yangtze River and the Guanzhong Plain belong to the third step.

3) The degree of coupling and coordination between China's urban science and technology finance and green development is generally positive spatial autocorrelation, and the spatial correlation is growing with time. Among the seven urban agglomerations, the coupling coordination degree of Beijing-Tianjin-Hebei, Yangtze River Delta and Pearl River Delta show a positive spatial autocorrelation. In contrast, the coupling coordination degree of other regions does not have a spatial correlation.
4) Science and technology finance, green development, and their coupling coordination are all affected by themselves. For science and technology finance and green development, the coupling and coordination degree impact on both is greater than the mutual impact between them. For the coupling coordination degree, the impact of science and technology finance is more significant than that of green development.

Based on the conclusions of this study, policy recommendations are presented in the following aspects. First, local governments should emphasize the positive externalities of scientific and technological financial policies on urban green development. Consider bringing cities with suitable innovation environments and substantial financial resources into the policy pilot scope. At the same time, when formulating relevant policies to promote urban green development, policymakers should actively guide various social capitals to support the green economy.

Second, considering the time-varying impact of science and technology finance policies on urban green development, local governments should formulate science and technology finance policies from a development and forward-looking perspective. In the policy implementation process, the government should give full play to its guiding role, scientifically evaluate the policy effect, and flexibly use the policy advantages to maximize the sustainable green development of the city. In addition, the introduction of policies should not be too hasty. There is a time lag between the implementation of policies and their effectiveness. Policymakers should avoid issuing too many policies of the exact nature in a short time.

Finally, differentiated policies should be formulated, considering regional imbalances in economic development and innovation. For eastern, high-level and innovative cities, it is necessary further to strengthen the combination of science and technology and finance and stimulate the policies of science and technology and finance to play a more prominent role. For cities in the central and western regions, low level and low innovation level, we should not only build a sound interaction mechanism between science and technology finance and economic development but also accelerate the introduction and application of advanced technology and give full play to its supporting role in driving urban green development.

Some study limitations must be considered when interpreting our findings. First, the evaluation indicator system and coupling model adopted in this study emphasize results and representations and lack in-depth exploration of the process mechanism. Second, the lack of data in some cities will lead to deviations in the statistical results. In our future research, we can explore the process mechanism of coupling through quantitative analysis of the internal relations between various systems. Additionally, we can use remote sensing technology, big data, and other new methods to obtain real-time relevant data to build a more comprehensive and comprehensive indicator system of science and technology finance and green development.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: China urban statistical yearbook, China economic net statistical database and EPS statistical database from 2003 to 2020.

Author contributions

CG: Conceptualisation, writing—original draft, formal analysis; MC: Data curation, methodology, software; YW: Visualization, investigation; CL: Writing—review and editing, supervision.

Funding

This paper is funded by the Projects of National Social Science Fund of China (20FJLB010).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 22 March 2023
DOI 10.3389/fenvs.2023.1116742

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OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Environmental Economics and Management,
a section of the journal
Frontiers in Environmental Science

RECEIVED 05 December 2022
ACCEPTED 06 March 2023
PUBLISHED 22 March 2023

CITATION
Zhu S, Sun J, Wu Y, Yu B, Li H, Xia T, Zhang X, Liang X and Zhu G (2023), A rural revitalization model based on regional livelihood capital: A case study of Diqing, China.
Front. Environ. Sci. 11:1116742.
doi: 10.3389/fenvs.2023.1116742

A rural revitalization model based on regional livelihood capital: A case study of Diqing, China

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Improving livelihood capital is beneficial for implementing China's rural revitalization strategy (RRS); however, researchers have not focused on the regional attributes of livelihood capital. Thus, this study proposes a new concept of regional livelihood capital to guide RRS implementation. A comprehensive measurement method and official government statistics were used to analyze regional livelihood capital characteristics in Diqing. The results demonstrate that, from 1993 to 2020, Diqing's regional livelihood capital index increased steadily from 0.058 to 0.356, and its structure continued to diversify; however, its level remains low. The natural capital index fluctuated between 2.044 and 2.284 and always had absolute advantages. The financial capital index increased rapidly from 0.024 to 1.396 and is the core driving force for the growth of regional livelihood capital. The physical capital index increased steadily from 0.056 to 0.456. The growth of the social and human capital index was slow and weak, with an average annual growth rate of only 4.42% and 1.07%, respectively, which represents a weakness in regional livelihood capital. Based on regional livelihood capital characteristics and Diqing's economic circumstances, a targeted rural revitalization model was developed according to the dynamics of the organic system of regional livelihood capital, in which natural capital is considered the foundation, financial capital is the power, physical capital is the medium, and social capital and human capital are the ultimate goals. The main direction of energy is "natural capital → financial capital → physical, social, and human capital." Simultaneously, reverse energy feedback should also be emphasized to promote the sustainable operation of this system. This study provides a new theoretical perspective of regional livelihood capital for the implementation of RRS and guidance for the practice of RRS in Diqing and other similar areas.

KEYWORDS

livelihood capital, regional livelihood capital, rural poverty, rural revitalization strategy (RRS), Diqing

1 Introduction

Rural poverty is an objective phenomenon in the history of human socioeconomic development (Tania, 2009; Shcherbak et al., 2020). Particularly, in developing countries, increasing urban polarization has caused rural areas to fall into a more desperate situation (Wang and Wan, 2015), leading to various problems, such as pressure on agriculture (Venables, 2018), infrastructure shortages (Onitsuka and Hoshino, 2018), and low incomes

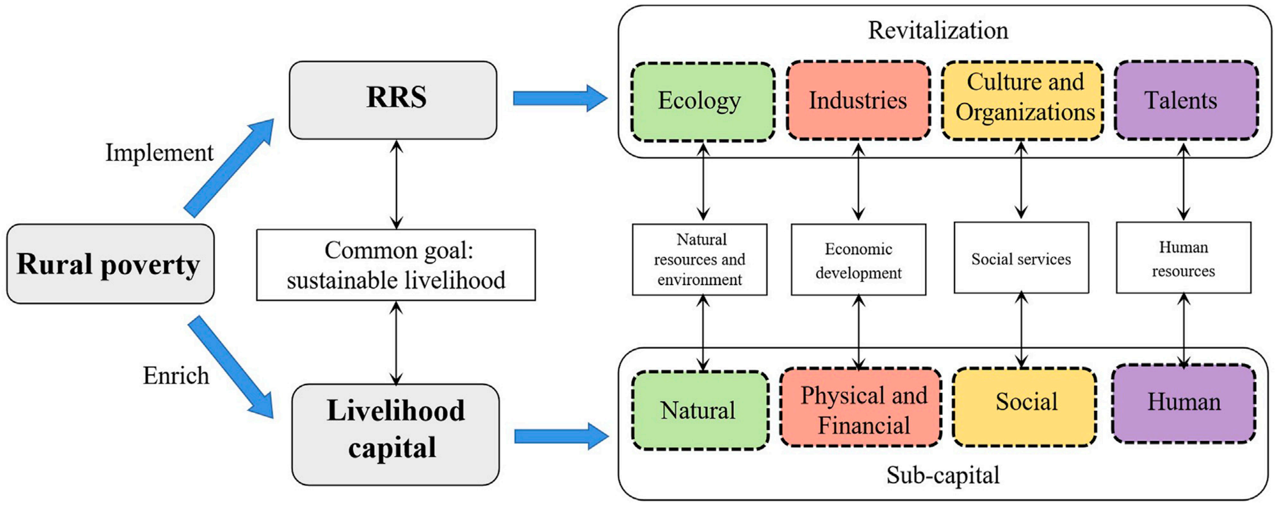

FIGURE 1
Links among rural poverty, the RRS, and livelihood capital.

for farmers (Africano and Collado, 2017). These problems have further exacerbated rural poverty. Subsequently, governments worldwide have implemented policies and measures to promote rural development (Marsden, 2010; Deng et al., 2022).

In China, the world's largest developing country, the government implemented policies that emphasized cities over rural areas to reverse the slow economic growth and low productivity that characterized the early days of China (Huang et al., 2020). Subsequently, the gap between urban and rural areas widened, and 80% of people living with long-term, large-scale, and intergenerationally transmitted poverty are concentrated in the vast rural areas (Liu M. et al., 2020). Although the Chinese government has made remarkable achievements in poverty alleviation, with 770 million people being lifted out of absolute poverty as of 2020, relative poverty persists in rural areas. To reduce poverty and promote the sustainable development of rural areas, the rural revitalization strategy (RRS), one of China's most important national development strategies (Liu, 2018), was first proposed at the 19th National Congress of the Communist Party of China in 2017. It aims to revitalize rural ecology, industries, culture, organizations, and talent to narrow the gap between urban and rural areas (Liu Y. et al., 2020). Compared with poverty alleviation focusing on poor rural areas, the RRS covers almost all rural areas and emphasizes positive interaction and integration between urban and rural areas at a macro-regional scale.

The RRS was proposed to solve the problem of rural poverty. The direct cause of poverty is the unsustainability of livelihoods (Scoones, 2009), which is fundamentally caused by the lack of livelihood capital (Roberts and Yang, 2003; Chowdhury, 2021). Livelihood capital is the sum of all available capital and conditions for people to make a sustainable livelihood (Wang et al., 2021a). It is the basis for resisting livelihood risks, choosing livelihood strategies, and achieving livelihood goals, as well as for policy intervention in rural development projects (Bhandari, 2013). Livelihood capital enrichment and RRS implementation are unified in value orientation, with the common goal of promoting the sustainability of people's livelihoods. In addition, the United Kingdom government's sustainable livelihoods approach (SLA) divides livelihood capital into natural, physical, financial, social, and human capital (DFID, 2000). These sub-capital forms are strongly linked to the RRS objectives (Figure 1). Both natural capital and ecological revitalization pertain to natural resources and the environment; physical capital, financial capital, and industrial revitalization focus on economic development; social capital and the revitalization of culture and organizations are aimed at social services; and human capital and the revitalization of talent focus on human resources (Liu M. et al., 2020; Chen et al., 2021). Therefore, livelihood capital can support the implementation of the RRS and provide a new theoretical perspective. It is an important theoretical basis for exploring the rural revitalization model.

As the core part of the SLA, livelihood capital has become the focus of many studies, mainly involving sustainable livelihoods (Marulanda et al., 2020; Yang et al., 2021; Azumah et al., 2022; Yan et al., 2022), poverty eradication (Zhang et al., 2020; Wang et al., 2021b), and public policy (Hua et al., 2017; Jin et al., 2021), and fruitful research results have been obtained. Subsequently, the five forms of sub-capital have become a popular research tool for quantitative measurement and an entry point for exploring relevant practical problems (Roberts and Yang, 2003; Chen et al., 2013; Zhang C. et al., 2019). However, most research has focused on micro-individuals (individuals or families) rather than macro-regions. Although the research on micro-individuals is significant for formulating personalized assistance measures for similar individuals, its instructiveness may be limited when implementing the RRS at a larger regional scale. Therefore, this study proposes the concept of regional livelihood capital to meet the practical needs of implementing the RRS and promote the use of livelihood capital in macro-regional research.

Diqing is one of the most representative and typical extreme poverty areas in China. Although Diqing has reduced absolute poverty (according to the poverty standard set by the Chinese

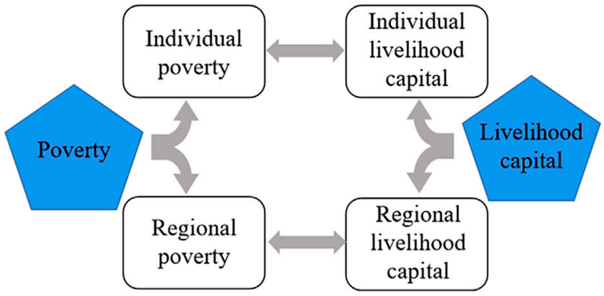

FIGURE 2
Basic contents of poverty and livelihood capital.

government in 2020), it still faces the risk of returning to poverty and the pressure of RRS implementation. Scientifically implementing the RRS to promote rural sustainability is a major issue for Diqing and urgently requires a response. Hence, this study uses the regional livelihood capital concept to develop a rural revitalization model for Diqing and provides a practical case for its use in RRS implementation. The main objectives of this study are as follows: 1) demonstrating the concept of regional livelihood capital; 2) using a reasonable evaluation index system, measurement method, and regional comparison to analyze the characteristics of regional livelihood capital; and 3) establishing a targeted rural revitalization model for Diqing as per the regional livelihood capital characteristics.

2 Demonstration of concepts

2.1 Individual and regional poverty

The original meaning of poverty refers to the lack of material items, money, and ability required to make a living among individuals, families, or specific groups (Konkel, 2014). With the development of poverty research, defining poverty from a geographical perspective has gained traction in academic discourse. Poverty is increasingly considered the result of a lack of geographical capital (Misturelli and Heffernan, 2010). Therefore, by examining poverty from different perspectives, individual and regional poverty have gradually become leading poverty concepts (Nallari and Griffith, 2011; Michálek and Madajová, 2019; Zhou and Liu, 2019; Hou et al., 2022). Individual poverty is defined using a micro-perspective and refers to the definition outlined previously. It also includes the deprivation of the right and opportunity to earn a living (Lo Bue and Palmisano, 2020). Regional poverty is defined using a macro-perspective as the decoupling of people, environment, and industry, focusing on the place where poverty occurs and the relationship between poverty and the environment (Liu et al., 2017). Individual and regional poverty affect each other, as individual poverty has a positive amplification effect and its accumulation will lead to regional poverty. In contrast, regional poverty caused by geographical disadvantage will also disadvantage individuals and further aggravate individual poverty. An analysis of individual poverty cultivates the endogenous development ability of people living in poverty, whereas an assessment of regional poverty is conducive to creating favorable development conditions in poverty regions. Subsequently, individual and regional poverty should be addressed to alleviate poverty.

2.2 Individual and regional livelihood capital

Poverty is the direct consequence of the long-term lack of livelihood capital (Su et al., 2009). According to the logic that poverty includes individual and regional poverty, livelihood capital can also include individual and regional livelihood capital. Just as the lack of individual livelihood capital causes individual poverty, regional poverty is also caused by the lack of regional livelihood capital (Figure 2).

Individual livelihood capital is the sum of all resources and conditions available for livelihood owned by an individual or family, and it emphasizes the private attributes of livelihood capital (Oladele and Ward, 2017). Individual livelihood capital is the focus of most current research and has been widely recognized in academia (Gentle and Maraseni, 2012; Fang et al., 2014; Liu and Xu, 2016; Xu et al., 2019). However, people's livelihood is closely related to their geographical environment. Different geographical environments will inevitably lead to different livelihood strategies and results, ultimately caused by the differences in regional livelihood capital in different regions (Berchoux and Hutton, 2019). Regional livelihood capital can be considered the sum of all resources and conditions available for livelihood provided by a specific regional environment (Xu et al., 2018). It emphasizes the regional attributes of livelihood capital. Regional livelihood capital focuses on the relationship between livelihood and the environment (Horsley et al., 2015). The regional livelihood capital amount can reflect the difficulty in making a living in specific regional environments.

In conclusion, both individual and regional livelihood capital are people-oriented. However, there are differences in the "people" they target. For individual livelihood capital, the word "people" refers to individuals or families, whereas regional livelihood capital regards "people" as all people in a specific region (Ghosh and Ghosal, 2021). Research on individual livelihood capital can explore how to develop sustainable livelihoods for individuals or families living in poverty (Liu et al., 2021a). Research on regional livelihood capital can explore sustainable development approaches (Singh and Hiremath, 2010). Thus, this study divides livelihood capital into natural, physical, financial, social, and human capital and distinguishes between individual and regional livelihood capital (Table 1).

3 Materials and methods

3.1 Study area

Diqing is a representative area of extreme poverty in China, with a weak foundation for rural development, making it an ideal case for this study. Its geographical environment is complex. Diqing is near the southwest border of China in Yunnan Province (Figure 3). It has an average altitude of 3,380 m, with 5,254 m between its highest and

TABLE 1 Differences between individual livelihood capital and regional livelihood capital.

Sub-capital	Differences in connotations	
	Individual livelihood capital	Regional livelihood capital
Natural capital	Natural resources and conditions that individuals or families can use to make a living (e.g., privately owned arable land, irrigation water, pasture, trees, and timber)	Natural resources and conditions provided by the regional geographical environment for people to make a living; this can be considered the natural background of people's livelihood (e.g., agricultural land, water resources, forests, and regional topography)
Physical capital	Physical material privately owned by individuals or families to make a living (e.g., vehicles, agricultural equipment, water conservancy facilities, and daily necessities)	The physical material conditions in the region that can support people's livelihood (e.g., consumer goods level, living conditions, and traffic conditions)
Financial capital	Funds consumed and accumulated by individuals or families to make a living (e.g., cash, deposits, wages, allowances, and relief funds)	The economic and financial conditions provided by the region to support people's livelihood (e.g., economic conditions, industrial level, residents' income level, fiscal revenue, and expenditure)
Social capital	All actual or potential social resources owned by individuals or families that can be used to make a living (e.g., marital status, interpersonal relationships, social organization, and culture/religion)	Social resources and conditions provided by the region to support people's livelihood (e.g., the degree of social development, social security, educational resources, medical resources, and cultural atmosphere)
Human capital	The physical functions and abilities of individuals or families, and the opportunities and rights to create their own value (e.g., individuals' physical qualities, skills, knowledge, and health status)	The quantity and quality of human resources on which regional development depends (e.g., regional population, labor force, education level, and employment opportunities)

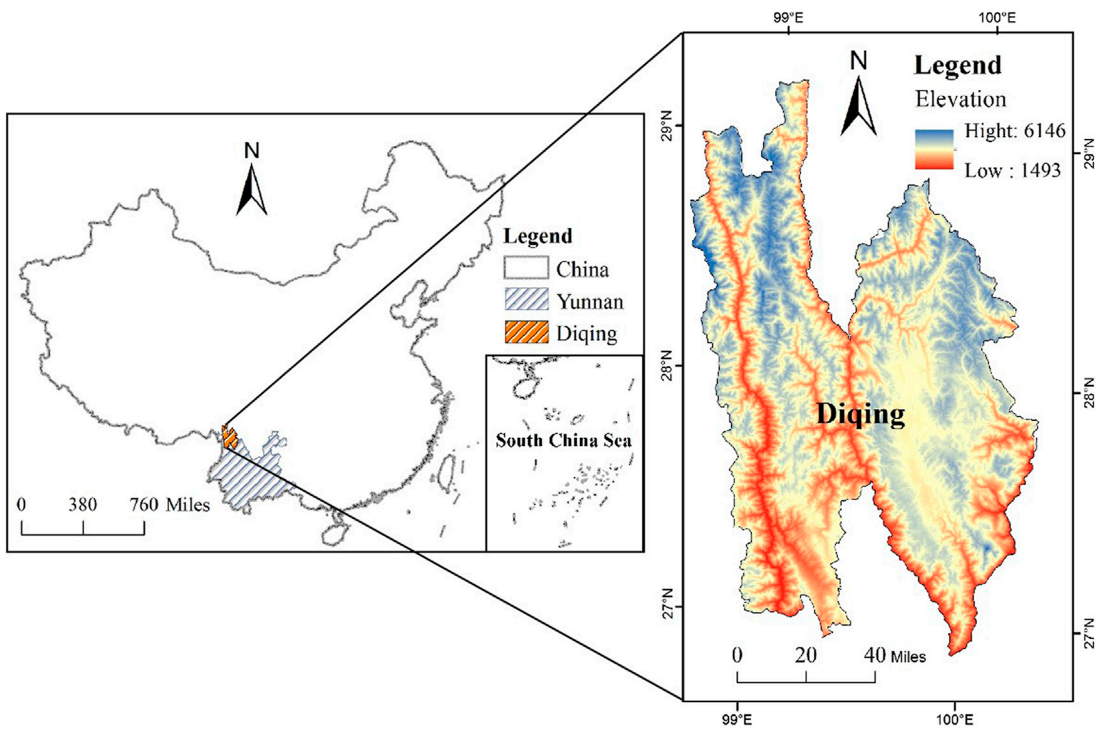

FIGURE 3
Map of Diqing in Southwest China.

lowest points; 94% of its area is mountainous, and 60% of the region has an area with a slope greater than 25°. It is characterized by surface fragmentation, vertical zonality, and a stereoscopic climate. The Lancang and Jinsha rivers run through Diqing from north to south, and most people living in poverty are scattered between more than 20 villages on both sides of these rivers. Mountainous natural conditions lead to a sparse population and a high cost of infrastructure construction and maintenance, which is one of the reasons for the lack of human and physical capital. In addition, the ecological security of Diqing is of great significance to China (Hillman, 2010), and the contradiction between ecological protection and economic development is prominent. However, the complex geographical environment is rich in natural resources, and owing to the location of the Hengduan Mountain tectonic belt, Diqing is a famous metal, rare metal, and non-metal mineral area in China. Diqing is also rich in biological resources and has unique tourism resources. These elements together embody Diqing's natural capital.

Diqing's socioeconomic development is also underdeveloped, with a low starting point for such development. In 1950, Diqing was liberated from the feudal serfdom society, and in 1978, with economic reform and opening up, it shifted from a planned economic system to a market economic system. In 1993, marked by the Poverty Alleviation Office Meeting held by the People's Government of Yunnan Province in Diqing, development in Diqing accelerated. Nevertheless, socioeconomic development remains underdeveloped. In 2020, Diqing achieved a total GDP of 26.694 billion yuan, comprising only 1.09% of the GDP from 6.06% of the land in Yunnan Province, and was ranked 15th among the 16 regions in the province. This has led to a neglect of financial and social capital in Diqing, as there has been insufficient investment in social services, such as education, medicine, and culture.

3.2 Data source

The data used in this study were obtained from the official statistics of local governments using the *Statistical Yearbook of Diqing*, *Yunnan Statistical Yearbook*, and *Statistical Communique of National Economic and Social Development*, which can be obtained from the official websites of the Yunnan Provincial Bureau of Statistics (http://stats.yn.gov.cn/) and the statistical information network of China (http://www.tjcn.org/). The research team had been engaged in the rural development of Diqing for a long time, established a good cooperative relationship with the relevant departments of the local government, and visited Diqing for field investigation and data collection in September 2018, August 2019, October 2020, and September 2021. In addition, the 1:500000 DEM datum of Yunnan Province used to calculate the relief degree of land surface (RDLS) was obtained from the geospatial data cloud website of the Computer Network Information Center of the Chinese Academy of Sciences (http://www.gscloud.cn), and the geographic coordinate system is WGS_1984_Albers. Basic data, such as average altitude, average elevation difference, flat area, and regional area, were calculated and extracted using ArcGIS10.2.

3.3 Methods

3.3.1 Comprehensive measurement of regional livelihood capital

In this study, regional livelihood capital was divided into natural, physical, financial, social, and human capital. The specific elements reflecting their characteristics were selected as evaluation indicators based on the following principles: 1) rationality and accessibility: the indicators should objectively reflect the level of regional livelihood capital, ensure the scientific nature of the evaluation results, and be obtained from authoritative official channels; 2) comprehensiveness and perspicacity: the indicators should comprehensively reflect the stock and quality of regional livelihood capital at the present stage and predict its future development trend; and 3) particularity and universality: the regional particularity of Diqing and its universality in horizontal comparison with other regions should be considered. On this basis and referring to previous studies, the natural capital indicators were natural resources (mainly agricultural) and natural environmental conditions (Hu, 2014); physical capital indicators were regional daily consumer goods, infrastructure, transportation, and housing (Fang et al., 2014); financial capital indicators were economic development and people's income in the region (Kuang et al., 2020); and social and human capital indicators were regional social security and social services (Naithani and Saha, 2020) and the quantity, quality, and employment of people in the region, respectively. Therefore, 26 indicators were selected to establish a regional livelihood capital evaluation index. The calculation method of each indicator is described in Table 2. The measurement of RDLS will be described separately, and the weights will be calculated using formula (2).

The regional livelihood capital evaluation index system is a comprehensive evaluation index system including five dimensions and 26 specific indicators. At present, there are few measurement methods specifically for regional livelihood capital, but the weighted summation, vector summation, and polygon area methods have achieved good results in relevant fields (Liu and Xu, 2016; Lind, 2019; Liu et al., 2021b). Among them, the weighted summation method is commonly used in one-dimensional measurements. The polygon area method is more suitable for an evaluation index system with more positive indicators and reflects the indispensability of all dimensions. Therefore, the weighted summation method measures each sub-capital, and the polygon area method integrates regional livelihood capital. The steps are outlined in the following paragraphs.

First, the range standardization method compares indicators with different units and dimensions (Dong et al., 2021). The formula is as follows:

$$\begin{aligned} &\textit{Positive indicators}: Z_{ij} = (X_{ij} - X_{\min})/(X_{\max} - X_{\min}),\\ &\textit{Negative indicators}: Z_{ij} = (X_{\max} - X_{ij})/(X_{\max} - X_{\min}), \end{aligned} \tag{1}$$

where Z_{ij} is the standardized value of the jth indicator of sub-capital i, X_{ij} is the original value of the jth indicator of sub-capital i, and X_{min} and X_{max} are the minimum and maximum of all data of the jth indicator of sub-capital i, respectively.

Second, in order to avoid artificial subjectivity and the irrationality of the equal weight method, the entropy method is used to objectively determine the weight of 26 indicators. The entropy method determines the weight according to the amount of information entropy carried by each indicator, which has been widely used in many studies (Ding et al., 2016; Zhao et al., 2018). Its algorithm is as follows:

$$\begin{aligned} &p_{ij} = \frac{Z_{ij}}{\sum_{i=1}^{n} Z_{ij}},\\ &e_{ij} = -k\sum_{i=1}^{n} p_{ij}\, ln\left(p_{ij}\right), k = 1/ln(n),\\ &d_{ij} = 1 - e_{j},\\ &w_{ij} = \frac{d_j}{\sum_{i=1}^{n} d_j}, \end{aligned} \tag{2}$$

TABLE 2 Evaluation index system of regional livelihood capital.

Sub-capital	Indicator	Calculation method	Weight	Property
Natural capital	Per capita land for agriculture use	Land for agriculture use/land area	0.0314	+
	Per capita amount of water resources	Total amount of water resources/total population	0.0638	+
	Index of wastes air pollution	Statistical data	0.0311	−
	Forest coverage	Statistical data	0.0304	+
	RDLS	Alt/1000+{ralt·[1-p(a)/a]}/500	0.0335	−
Physical capital	Per capita retail sales of consumer goods	Retail sales of consumer goods/total population	0.0426	+
	Per capita rural investment in fixed assets	Rural investment in fixed assets/rural population	0.0441	+
	Per capita floor space completed	Floor space completed/total population	0.0335	+
	Highway density	Total length of highways/land area	0.0408	+
	Per capita private motor vehicles	Total private motor vehicles/total population	0.0352	+
Financial capital	Per capita gross regional product	Statistical data	0.0336	+
	Per capita gross agricultural output value of agricultural population	Gross agricultural output value/agricultural population	0.0420	+
	Average savings deposit balance of rural households at year-end	Balance of rural household savings deposits at year-end/ number of rural households	0.0415	+
	Disposable income *per capita* of rural residents	Statistical data	0.0385	+
	Per capita final consumption expenditure of rural households	Final consumption expenditure of rural households/rural population	0.0403	+
	Per capita local government general budgetary expenditure	Local government general budgetary expenditure/total population	0.0339	+
Social capital	Urbanization rate	Statistical data	0.0390	+
	Coverage of rural subsistence allowances	Rural subsistence allowance population/rural population	0.0348	−
	Per capita expenditures on culture and cultural relics	Expenditures on culture and cultural relics/total population	0.0406	+
	Number of regular institutions of higher education	Statistical data	0.0405	+
	Number of hospital beds *per capita*	Number of hospital beds/total population	0.0377	+
Human capital	Total population	Statistical data	0.0409	+
	Proportion of non-agricultural population	Non-agricultural population/total population	0.0392	+
	Proportion of rural employed persons	Rural employed persons/rural population	0.0371	+
	Proportion of scientists and technicians	Scientists and technicians/total population	0.0352	+
	Average educational years of rural residents	Statistical data	0.0388	+

where p_{ij} is the proportion of the *j*th indicator value of sub-capital *i*, e_{ij} is the entropy of the *j*th indicator of sub-capital *i*, d_{ij} is the information entropy redundancy of the *j*th indicator of sub-capital *i*, and w_{ij} is the weight of the *j*th indicator of sub-capital *i*.

Third, the weighted summation method is used to measure the sub-capital index:

$$Nci, Pci, Fci, Sci, Hci = \sum_{i=1}^{n} w_{ij} \cdot z_{ij}, \quad (3)$$

where *Nci* is the natural capital index, *Pci* is the physical capital index, *Fci* is the financial capital index, *Sci* is the social capital index, *Hci* is the human capital index, w_{ij} is the weight of the *j*th indicator of sub-capital *i*, Z_{ij} is the standardized value of the *j*th indicator of sub-capital *i*, and *n* is the indicator quantity of sub-capital *i*.

Finally, the polygon area method integrates the regional livelihood capital index. This method is an approach for comprehensive measurements. It extends outward with multiple lines of common points to form a polygon, and the length of these lines is regarded as the value of each dimension. In contrast, the area of the polygon is regarded as the value of the comprehensive measure (Liu and Xu, 2016). The five sub-capital forms are drawn as five lines with common points to form a regional livelihood capital pentagon (Figure 4).

In Figure 4, *O* is a common point, and *Nc*, *Pc*, *Fc*, *Sc*, and *Hc* represent natural, physical, financial, social, and human capital, respectively. α is the included angle of five lines ($\alpha = 360^{\circ}/5 = 72^{\circ}$), and the area of pentagonal *NciPciFciSciHci* is defined as the regional livelihood capital index (RLCI). According to the relevant geometric knowledge, the calculation is as follows:

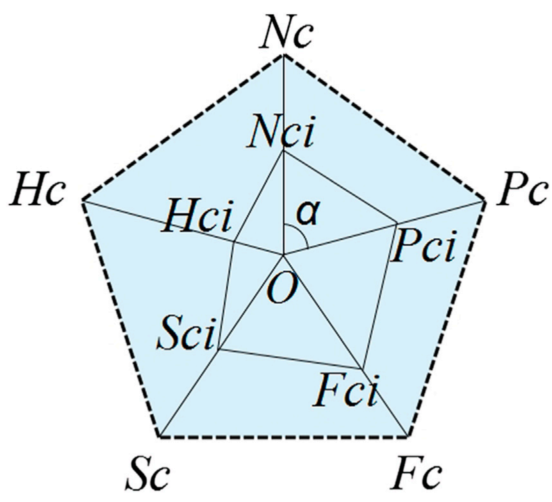

FIGURE 4
Regional livelihood capital pentagon.

$$RLCI = \frac{1}{2}\sin\alpha \left(Nci \cdot Pci + Pci \cdot Fci + Fci \cdot Sci + Sci \cdot Hci + Hci \cdot Nci\right). \quad (4)$$

3.3.2 Relief degree of land surface

RDLS comprehensively represents regional altitude and surface fragmentation and is one of the important indicators for geomorphological classification (Feng et al., 2008). Some extant studies have proven that there is a significant negative correlation between RDLS and regional socioeconomic development (Liu et al., 2015; Zhang J. et al., 2019). Particularly, in the mountainous Yunnan Province, the obstacles of land surface relief to regional socioeconomic development are more prominent (Zhu et al., 2020). As a natural geographical representation, large RDLS will inevitably lead to natural capital disadvantage, so it is considered an important indicator for evaluating natural capital. The formula is as follows:

$$RDLS = RAA/1000 + \{RAED \times [1 - FA/A]\}/500, \quad (5)$$

where RAA is the regional average altitude, $RAED$ is the regional average elevation difference, FA is the flat area of the region (according to the mapping standard of the China geomorphic map, an elevation difference of less than or equal to 30 m is regarded as flat (Feng et al., 2008)), and A is the area of the region.

3.3.3 Contribution degree of indicator

The contribution degree of indicator (CDI) is a quantitative evaluation of the effect of each indicator on the evaluation results to identify the importance of these indicators (Alkire and Foster, 2011a). It can also be used to quantitatively describe the impact of different dimensions on the measurement results (Alkire and Foster, 2011b). In this study, CDI is used to explore the impact of various indicators on regional livelihood capital to identify meaningful indicators and reflect the development trend of the contribution of natural, physical, financial, social, and human capital to regional livelihood capital. The formula is as follows:

$$CDI_{ij} = \frac{w_{ij} \cdot z_{ij}}{\sum_{i=1}^{n} w_{ij} \cdot z_{ij}} \times 100\%, \quad (6)$$

where CDI_{ij} is the contribution degree of indicator of the jth indicator of sub-capital i, w_{ij} is the weight of the jth indicator of sub-capital i, and Z_{ij} is the standardized value of the jth indicator of sub-capital i.

3.3.4 Diversification index

The diversification index (DI) is used to quantitatively describe the diversification degree of regional livelihood capital, that is, the proportional relationship and equilibrium degree of each sub-capital that comprises regional livelihood capital (Yang et al., 2014; Shahzad et al., 2021). Because this study involves the five forms of sub-capital, the maximum DI is 0.8 (1–1/5 = 0.8), and the minimum is infinitely close to 0. DI depends on the inequality of different dimensions (natural, physical, financial, social, and human capital). The higher the DI, the stronger the stability of the regional livelihood capital structure. The formula is as follows:

$$DI = 1 - \sum_{i=1}^{5}\left[\frac{V_i}{Nci + Pci + Fci + Sci + Hci}\right]^2, \quad (7)$$

where DI is the diversification index of regional livelihood capital, V_i is the value of ith sub-capital index, Nci is the natural capital index, Pci is the physical capital index, Fci is the financial capital index, Sci is the social capital index, and Hci is the human capital index.

These methods consider the time series from 1993 to 2020 (the period of rapid development of Diqing). The raw data of each year need to be obtained and used to calculate the relevant index (except RDLS because 23 years is too short for RDLS, and its change can be ignored).

4 Results

4.1 Analysis of the development of regional livelihood capital

The measurement results of RLCI in Diqing are illustrated in Figure 5. From 1993 to 2020, Diqing's RLCI increased steadily from 0.058 to 0.356, with an average annual growth rate of 6.98%. During this period, the growth rate was relatively slow, with an average annual growth rate of 4.98%. From 2009 to 2020, mainly due to the rapid development of financial capital, the RLCI entered a period of rapid growth, with an average annual growth rate of 10.25%.

Natural capital fluctuates significantly. From 1993 to 2020, Nci fluctuated between 2.044 and 2.284, with a slight increase. This reflects that the ecological and environmental protection policies and measures in Diqing have, to a certain extent, succeeded in promoting natural capital. From the CDI, the change in the "per capita amount of water resources" is the key factor causing the fluctuation of natural capital, as illustrated in Figure 6A. In 2001, 2006, 2009, 2010, and 2016, Diqing suffered drought, resulting in water shortages; in 2010, the drought threatened the livelihood of some peasant households. Overall, the CDI of the five natural capital indicators is trending downward, with the "per capita amount of water resources" decreasing most significantly.

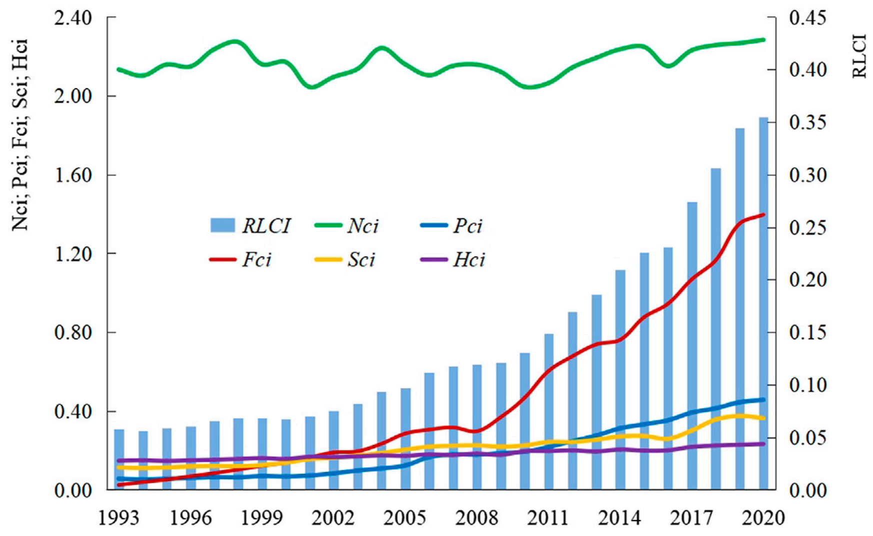

FIGURE 5
Development of regional livelihood capital in Diqing (1993–2020).

Physical capital grew steadily. From 1993 to 2020, *Pci* gradually increased from 0.056 to 0.456, with an average annual growth rate of 8.08%. Particularly, after 2010, the growth trend is more obvious. From the CDI, the five physical capital indicators are rising, as illustrated in Figure 6B, with the "per capita rural investment in fixed assets" and "per capita retail sales of consumer goods" increasing significantly, demonstrating that fixed assets and daily consumer goods are the key factors for the growth of physical capital. These findings indicate that, since 2010, the measures implemented to increase fixed asset investment and promote poverty alleviation have led to the rapid development of rural life and production infrastructure in Diqing, which are critical to the growth of physical capital.

Financial capital increased significantly. *Fci* increased rapidly from 0.024 to 1.396, with an average annual growth of 16.24%. Particularly, since 2003, *Fci* has maintained a high growth rate. Based on the CDI, the six financial capital indicators show a rapid growth trend, as illustrated in Figure 6C, with the "per capita gross agricultural output value of agricultural population" increasing the most, indicating that agriculture is key to the rapid growth of financial capital. In the past 40 years, Diqing has gradually transitioned from pure manual labor to semi-mechanization, and the rapid development of the agricultural economy has increased farmers' income. In addition, the CDI of each index fluctuated slightly in 2008, possibly due to the global financial crisis and frost disasters.

Social capital grew relatively slowly. *Sci* increased from 0.113 to 0.363, with an annual growth rate of 4.42%. From the CDI, the five social capital indicators have different trends, as illustrated in Figure 6D. The "per capita expenditures on culture and cultural relics" and "number of hospital beds *per capita*" increased significantly, the "urbanization rate" increased slightly, and the "coverage of rural subsistence allowances" decreased gradually. This demonstrates the continuous improvement of cultural, medical, and educational service capabilities and the steady growth of farmers' income. However, there is currently no regular higher education institution in Diqing, which is extremely unfavorable for the growth of social capital.

Human capital grew weakly; *Hci* increased slowly from 0.147 to 0.232, with an annual growth rate of only 1.70%. Based on the CDI, the five human capital indicators have different development trends, as illustrated in Figure 6E. "Total population," "proportion of scientists and technicians," and "average educational years of rural residents" decreased slightly, whereas the "proportion of non-agricultural population" and "proportion of rural employed persons" increased slightly. This suggests that the development of non-agricultural industries and farmers' employment increasingly impacts human capital. Much attention should also be paid to the introduction of talent and the extension of farmers' education.

4.2 Analysis of the structure of regional livelihood capital

The sub-capital indexes from 1993 to 2020 are illustrated in Figure 7A. The proportion of sub-capital gradually tends to be relatively balanced, and the structure of regional livelihood capital is developing toward diversification. From the CDI, natural capital has decreased significantly, from 86.25% to 48.28%, but still occupies an absolute advantage; physical capital increased steadily from 2.26% to 9.64%; financial capital increased rapidly and substantially from 0.97% to 29.51%; social capital was relatively stable and fluctuated slightly, increasing from 4.57% to 7.67%; and human capital decreased from 5.94% to 4.90% in slight fluctuations. These trends indicate that natural capital has always been the basic element in regional livelihood capital's continuous growth, and regional economic development cannot be separated from the dependence on natural capital. In addition, regional livelihood capital DI rose from 0.2498 to 0.6623, as illustrated in Figure 7B. This demonstrates that regional livelihood welfare has become more

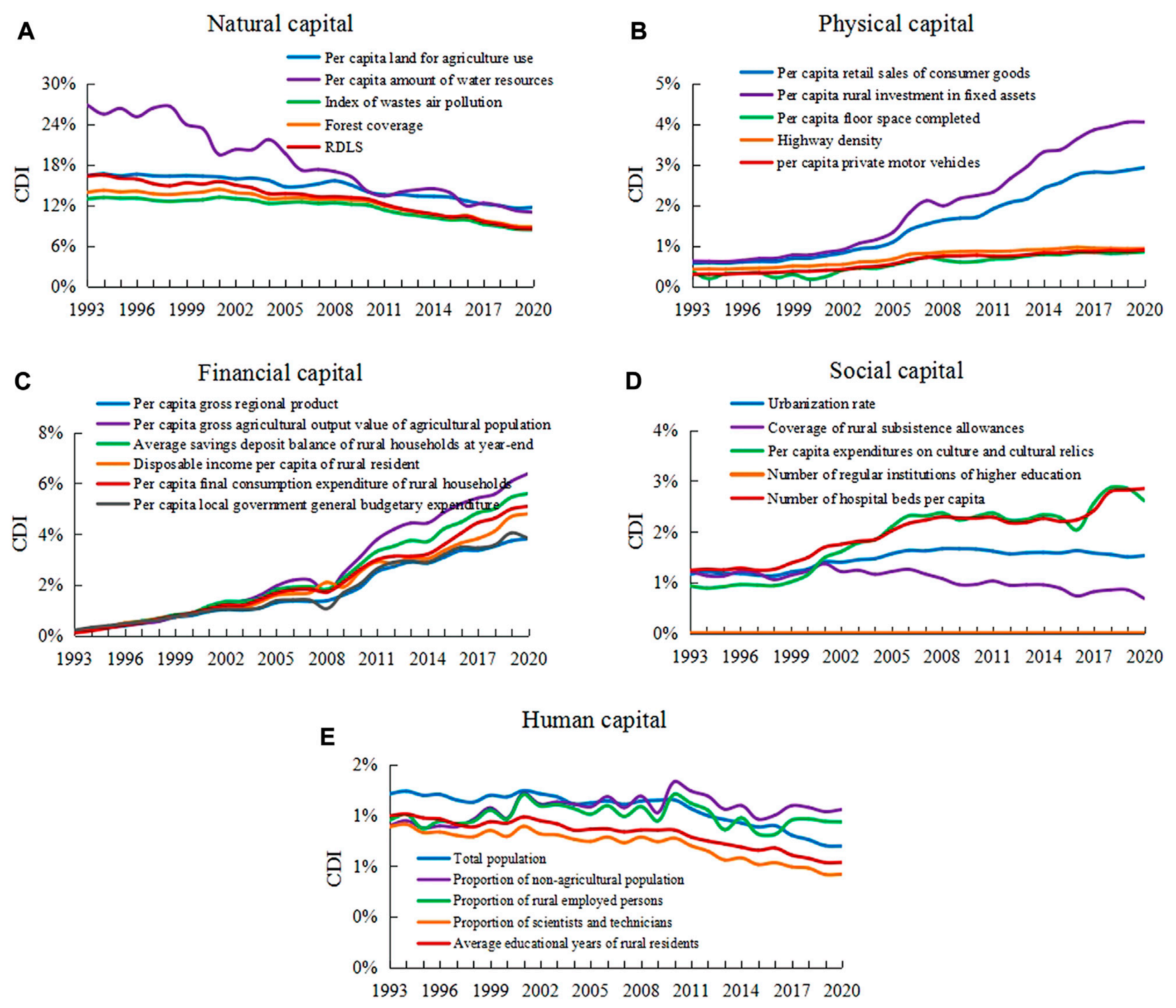

FIGURE 6
Development of CDI in Diqing (1993–2020). **(A)** Natural capital. **(B)** Physical capital. **(C)** Financial capital. **(D)** Social capital. **(E)** Human capital.

diversified, and the stability of the livelihood capital structure has improved.

From 1993 to 2020, the regional livelihood capital structure of Diqing evolved from "natural—human—social—physical—financial" to "natural—financial—physical—social—human." Although the stability of the regional livelihood capital structure was strengthened, it is still unreasonable and requires further optimization. The proportion of natural capital remains large, demonstrating that the natural environment can provide resources for people's livelihood, which is the foundation and advantage of Diqing. However, it also shows that people's livelihood depends too much on natural resources, which is unsustainable if not managed effectively. Additionally, the weakness of human, social, and physical capital are obstacles to the continuous optimization of the regional livelihood capital structure.

4.3 Comparative analysis of Diqing and other regions

This study compares Diqing with other regions in Yunnan Province to clarify the comparative characteristics of Diqing's regional livelihood capital. As illustrated in Table 3, in 2020, the RLCI of Diqing ranked 15th among the 16 regions in Yunnan Province at 0.355, indicating that the level of regional livelihood capital in Diqing was relatively low. For sub-capital, *Nci* ranked first in the province with 2.284, indicating that the comparative advantage of natural capital was significant. In particular, the *per capita* amount of water resources is as high as 28731.96 m^3, which is 7.5 times that of Yunnan Province and 12.7 times that of the country. *Pci* and *Fci* ranked 15th with 0.456 and 1.396, respectively, indicating a serious shortage of physical and financial capital. In particular, the *per capita* gross agricultural output value of the agricultural population in

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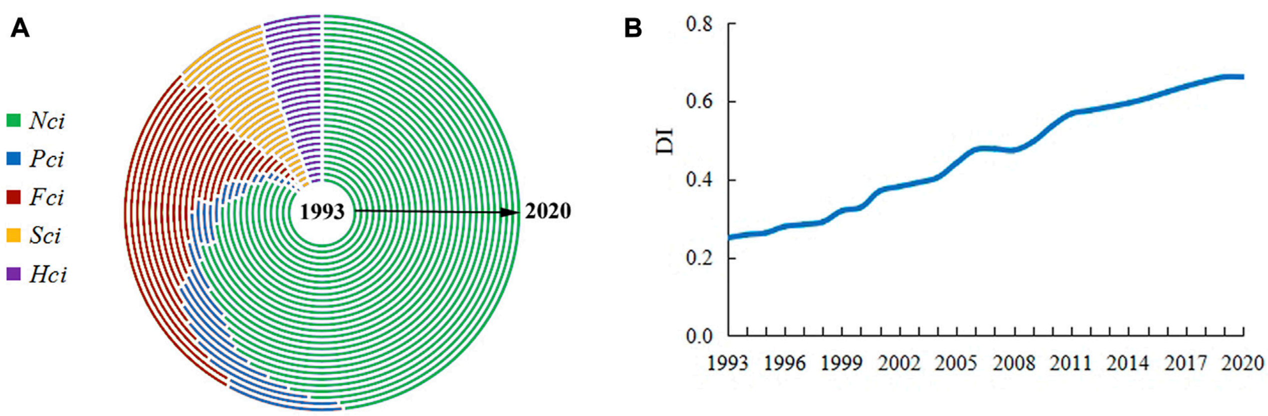

FIGURE 7
Development of the regional livelihood capital structure in Diqing (1993–2020). **(A)** Regional livelihood capital structure. **(B)** Regional livelihood capital DI.

TABLE 3 Regional livelihood capital of 16 regions in Yunnan Province in 2020.

Region	RLCI	Rank	*Nci*	Rank	*Pci*	Rank	*Fci*	Rank	*Sci*	Rank	*Hci*	Rank
Diqing	0.355	15	2.284	1	0.456	15	1.396	15	0.363	16	0.232	16
Kunming	5.462	1	0.923	11	3.230	1	4.901	1	2.872	1	2.672	1
Honghe	2.130	2	0.942	10	2.304	2	2.953	4	1.463	4	1.452	3
Yuxi	2.041	3	0.882	12	2.078	4	3.256	2	1.494	3	1.102	9
Qujing	1.872	4	0.386	16	2.157	3	3.015	3	1.518	2	1.494	2
Dali	1.838	5	1.235	3	2.018	5	2.604	6	1.310	5	1.306	5
Chuxiong	1.718	6	0.836	13	1.958	6	2.902	5	1.228	6	1.286	6
Wenshan	1.231	7	0.711	14	1.758	7	2.263	7	1.006	9	1.276	7
Baoshan	1.147	8	1.156	6	1.298	9	2.094	9	1.098	7	1.118	8
Zhaotong	1.057	9	0.505	15	1.537	8	2.164	8	1.026	8	1.310	4
Pu'er	0.840	10	1.161	5	1.112	10	1.951	10	0.681	11	0.992	11
Lincang	0.727	11	1.195	4	0.954	12	1.638	14	0.630	12	1.091	10
Xishuangbanna	0.679	12	0.982	8	1.083	11	1.711	13	0.774	10	0.630	13
Dehong	0.598	13	0.962	9	0.928	13	1.880	12	0.534	13	0.714	12
Lijiang	0.509	14	1.054	7	0.818	14	1.909	11	0.470	14	0.452	14
Nujiang	0.317	16	1.984	2	0.419	16	1.226	16	0.390	15	0.285	15

Diqing is only 11408.24 yuan, far less than 25101.76 yuan in Yunnan Province and 24607.14 yuan in the country. *Sci* and *Hci* ranked last with 0.363 and 0.232, respectively, indicating that the most serious problems were the lack of social and human capital. In particular, the number of hospital beds in Diqing is only 4.87 per thousand people, lagging behind 6.89 in Yunnan Province and 6.45 in the country. The total population of Diqing is only 38,751, the smallest of the 16 regions in Yunnan Province, and the quantity and quality of human capital are seriously insufficient.

5 The rural revitalization model for Diqing

The comprehensive measurement results indicate that, although Diqing's regional livelihood capital has steadily increased and the structure has been continuously optimized, the quality remains low and needs to be improved. Although natural capital fluctuates, its advantages remain significant. It is the foundation of Diqing's regional livelihood capital. The rapid growth of financial capital is the key to improving the quality and structure of regional

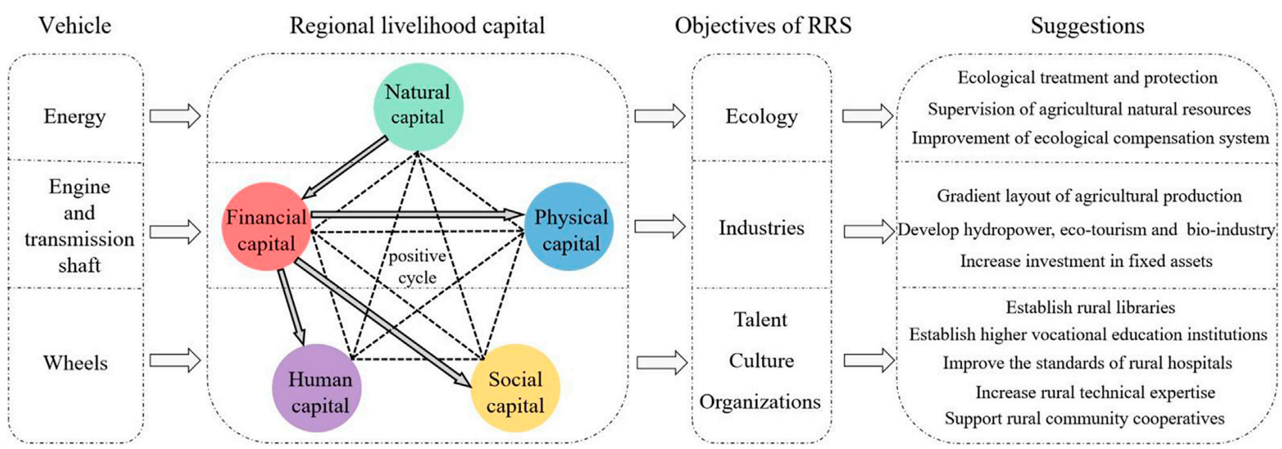

FIGURE 8
Rural revitalization model in Diqing.

livelihood capital, which is the core driving force for promoting the development of Diqing. However, there is a shortage of this compared to other regions. Physical capital is growing steadily, and its contribution to regional livelihood capital is also increasing. However, it remains insufficient compared with other regions. With their weak growth, social capital and human capital are at a disadvantage compared with other regions and are weaknesses in Diqing's regional livelihood capital. In terms of actual economic development, the proportion of primary, secondary, and tertiary industries in Diqing in 2020 was 6.2:37.9:55.9, which seems to contradict its underdeveloped economy. Furthermore, the advanced development of tourism has resulted in a single tertiary industry in Diqing. However, the role of the secondary industry, mainly manufacturing, in promoting socioeconomic development has not emerged yet. Meanwhile, the tertiary industry dominated by tourism cannot drive the primary and secondary industries. The high level of the tertiary industry in Diqing does not represent a developed economy but is the result of a "virtualization" of the industrial structure (Chen et al., 2016). Improving farmers' livelihoods fundamentally depends on the primary industry (agriculture), which is most closely related to their livelihood. The primary industry (agriculture) plays an important basic role in improving farmers' livelihoods. However, relying on agriculture is insufficient. It needs to form a joint force with other industries to promote the RRS implementation in Diqing. Fortunately, when other forms of sub-capital are at a disadvantage, abundant natural capital provides many possibilities to develop various industries. To sum up, RRS implementation in Diqing must rely on the development and utilization of natural capital.

Based on the linkages between regional livelihood capital and the RRS objectives, the comprehensive measurement results and economic information analysis, the principle of system dynamics (Ravar et al., 2020), and the people-oriented concept, this study regards regional livelihood capital as an organic system formed by the coupling of natural, physical, financial, social, and human capital. For Diqing, if the organic system is compared to a vehicle, natural capital can be regarded as energy, financial capital as the engine, physical capital as the transmission shaft, and human capital and social capital as the wheels. Its goal is to make the car move fast and smoothly, that is, to make the wheels turn faster and more stably. Therefore, a targeted rural revitalization model was developed for Diqing according to the linkages between the forms of sub-capital and the RRS objectives (Figure 8).

The details of the model are based on several recommendations. First, continuing to consolidate the advantages of natural capital and promoting ecological revitalization are important. Natural capital is the foundation of Diqing's regional livelihood capital and socioeconomic development, just as a vehicle needs sufficient and high-quality energy to continue moving. Ensuring ecological security and sustainable utilization of natural resources are the primary tasks for RRS implementation. Ecological revitalization is the premise of rural revitalization. Therefore, this study recommends that ecological treatment and protection projects be carried out, with an emphasis on returning farmland to forest and grassland, protecting natural forests, and preventing and controlling environmental pollution. More attention should be paid to the supervision of agricultural and natural resources to ensure the supply of farmers' natural means of production. The ecological compensation system should be improved so that farmers can directly benefit from ecological protection.

Second, natural capital should be transformed into financial capital to promote industrial revitalization. This is the process by which the engine converts energy into kinetic energy. However, this does not mean seeking economic growth at the cost of environmental pollution and resource destruction. Instead, it follows the concept of sustainable development to emphasize the green utilization of natural resources and the development of industries according to local conditions. Moreover, the gradually enriched financial capital can provide more economic support for the consolidation of natural capital. Therefore, ecological and industrial revitalization can be promoted simultaneously, which is a key task for RRS implementation. Judging from the development of the regional livelihood capital structure, Diqing is possibly at this stage now. This study suggests that agricultural production should be distributed professionally according to the altitude of a given area: high-altitude agricultural industry (highland barley, potato, Tibetan pig, yak, etc.) should be developed on plateaus; under-forest planting and breeding (medicinal materials, walnuts, cattle, sheep, poultry, etc.) and wild animal domestication (wild boar, Tibetan pheasant, etc.) should be developed in mountainous areas; and specialized planting (rice, corn, grape, tobacco, silkworm, etc.) and large-scale livestock and poultry breeding should be vigorously promoted in valleys. Green energy (hydropower), ecotourism, and agricultural bio-industry should be developed to increase income. Furthermore, investment in fixed assets should be increased to improve infrastructure, and priority should be given to irrigation and water conservation, transportation, factories, and other production facilities to improve economic efficiency and promote the growth of the real economy. More importantly, investment in natural ecological protection should be guaranteed.

Finally, financial capital, which is gradually enhanced, should be appropriately transformed into physical, social, and human capital to promote the revitalization of organizations, culture, and talent. The accumulation of financial capital is not the goal. However, its strong convertibility should be used to reasonably adjust the regional livelihood capital structure and enhance the ability to resist external risk shocks. This is how the engine transmits kinetic energy to the wheels, in which physical capital plays an important role. The support from physical materials, such as fixed assets and consumer goods, can greatly improve the output efficiency of financial capital and connect the channel of energy transmission from financial capital to social, human, and natural capital to increase the operational efficiency of the whole organic system. The accumulation of social and human capital is the goal of the operation of the organic system, but it is not the terminal of energy transmission. Social progress and the improvement of population quality complement each other, which produces positive energy feedback on natural, financial, and physical capital. Such a positive cycle will fundamentally strengthen the integration of regional livelihood capital and provide sustainable energy RRS implementation in Diqing. Therefore, this study recommends that actions be taken to establish rural libraries, launch higher vocational education institutions, improve the standards of rural hospitals, promote technical expertise in rural areas, and support rural community cooperatives. In this way, social progress and the improvement of population quality will, in turn, provide services for ecological protection and economic development.

In conclusion, in the organic regional livelihood capital system, the main direction of energy is "natural capital → financial capital → physical capital, social capital, and human capital," but at the same time, there is positive reverse return energy, which needs to be the focus. Therefore, it is necessary to promote the positive energy cycle among the five forms of sub-capital and ensure the efficient and stable operation of this organic system. In this way, the objectives of the RRS can also be achieved in this process.

6 Discussion

As one of the most representative poverty-stricken areas in China, Diqing is facing the practical problem of how to effectively implement the RRS. Many studies have provided solutions from different perspectives, such as improving the system construction (Lu et al., 2020), developing ecotourism (Bai and Ren, 2021), and enriching people's spiritual world (Coggins, 2019). Therefore, it is necessary to consider the RRS implementation from a more comprehensive perspective. Livelihood capital is composed of natural, physical, financial, social, and human capital, which is highly linked with the objectives of the RRS, providing an effective perspective for RRS implementation. Based on this, the model and relevant policy recommendations developed in this study have certain practical contributions for RRS implementation in Diqing and other similar areas.

Based on the current situation, in which livelihood capital research focuses on micro-individuals and ignores macro-regions, this study puts forward a new concept of regional livelihood capital to meet the practical needs of the RRS and creatively expounds its concept and connotation. Compared with the concept of individual livelihood capital pursued by mainstream studies, regional livelihood capital regards people in a specific region as a "whole" to emphasize the relationship between people's livelihood and the environment. However, some indicators with regional attributes have been included in the livelihood capital evaluation index system in some previous studies to reflect regional differences, such as "*per capita* mineral resource reserves," "regional fiscal revenue," "total regional population," "number of subsistence allowances," and "per capital area under culture" (Hu, 2014; Wu et al., 2019; Paul et al., 2020). These indicators reflect the inevitable connection between people's livelihood and the regional environment, demonstrating this study's theoretical contribution: livelihood capital is made up of both individual and regional livelihood capital. This can further enrich the connotation of livelihood capital and may also increase the understanding of livelihood capital in studies using a macro-regional perspective. It also provides new theoretical guidance for RRS implementation.

Based on the linkages between the forms of sub-capital and the objectives of the RRS, this study uses regional livelihood capital to develop a rural revitalization model for Diqing. It holds that the main direction of energy is "natural capital → financial capital → physical capital, social capital, and human capital" and that different sub-capitals play different roles. 1) Natural capital is the foundation. For Diqing, ecological revitalization is the premise of rural revitalization. This view is similar to a study in Iran, which demonstrated that natural capital plays a crucial role in the livelihood level and ecosystem function of residents in Zarivar (Aazami and Shanazi, 2020). 2) Financial capital is the core driving force of regional livelihood capital enrichment and should be the focus of the RRS. This is similar to a study in Sapa, Vietnam, which demonstrated that the convertibility of farmers' financial capital could better promote other forms of sub-capital to improve their livelihood strategies (Huang et al., 2022). 3) While physical capital plays a medium role, the development of other forms of sub-capital must include physical materials. This is similar to results from a study in Chiapas, Mexico, which demonstrated that when farmers adapt to climate change, physical capital guarantees that other sub-capital forms will play a more effective role (Shinbrot et al., 2019). 4) The improvement of social and human capital is the ultimate goal of RRS implementation. This is similar to the view of a study conducted in Bangladesh that demonstrated that the sustainability of social and human capital is fundamental to the protection of forest resources (Islam et al., 2019). In particular, many other studies have confirmed the foundation of natural capital, the convertibility of financial capital, the intermediary nature of physical capital, and the intangibility of social capital (Karunarathne and Lee, 2019; Mbiba et al., 2019; Yang et al., 2021). Some studies hold different views from this study (Guo et al., 2019; Wang et al., 2021a); however, they should be interpreted in consideration of their specific situation.

Although most studies focus on individual livelihood capital, whether their findings are similar to this study largely depends on whether the study area is similar in the geographical environment and economic and social development. To take it a step further, livelihood capital has regional attributes, and the operation mode of the organic system of livelihood capital has spatial heterogeneity. Subsequently, the research on individual or regional livelihood capital should be based on a specific geographical environment. Therefore, the rural revitalization model developed in this study is not universal but is only effective for Diqing or areas similar to Diqing, which is one of its limitations. Other different types of regions need to be specifically analyzed according to the characteristics of their regional livelihood capital and geographical environment. In addition, this study uses prefecture-level regions as the research scale. Although some discoveries were made, other potential links may be found at the provincial, county, or village levels, and the research team intends to investigate this further. Moreover, most of the data in this study are based on official statistics, and the problems reflected may be relatively macro and even limited. More importantly, however, this study uses the linkages between livelihood capital, the RRS, and the principle of system dynamics to develop a rural revitalization model. This idea can be replicated in other regions to guide rural development. Following this idea, there are some possible research directions in the future, for example, performing quantitative analysis of the interaction of sub-capital forms, or examining how to comprehensively consider individual and regional livelihood capital, using statistics and field survey data to improve the livelihood capital evaluation index system, and formulating reasonable RRS policies according to the operation model of the regional livelihood capital organic system.

7 Conclusion

This study introduces a new concept of regional livelihood capital to develop an evaluation index system to analyze the characteristics of regional livelihood capital in Diqing. The results demonstrate that, from 1993 to 2020, Diqing's regional livelihood capital increased steadily, and the livelihood capital structure continued to diversify, but the level remained low. Although natural capital fluctuates in terms of sub-capital forms, it still has absolute advantages and is the foundation of regional livelihood capital. The rapid growth of financial capital is the core driving force for the growth of regional livelihood capital. The growth of physical capital is stable, but it is insufficient compared with other regions. The weak growth of social and human capital is the weakness of regional livelihood capital.

Based on the results of the comprehensive measurement of regional livelihood capital and the economic information of Diqing, following the principle of system dynamics and the concept of being people-oriented, a targeted rural revitalization model was developed that regards regional livelihood capital as an organic system formed by combining natural, physical, financial, social, and human capital. Among these, natural capital is the foundation (energy), financial capital is the power (engine), physical capital is the medium (bearing), and social capital and human capital are the goals (wheels). The main direction of energy is "natural capital → financial capital → physical capital, social capital, and human capital." Moreover, the reverse feedback of energy should also be given much attention to promote sustainability and coordinate the efficient operation of this organic system. This model can provide significant guidance for RRS implementation in Diqing and other similar poor areas. Importantly, regional livelihood capital provides a theoretical perspective for sustainable rural development.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found at: Yunnan Provincial Bureau of Statistics (http://stats.yn.gov.cn/); the statistical information network of China (http://www.tjcn.org/); and Computer Network Information Center of the Chinese Academy of Sciences (http://www.gscloud.cn).

Author contributions

SZ: conceptualization, methodology, formal analysis, investigation, and writing—original draft. JS: supervision and funding acquisition. YW: investigation and writing—review and editing. BY: methodology. HL: investigation. TX: software and data collection. XZ: data collection. XL: data collection. GZ: data collection.

Funding

This work was supported by the National Social Science Fund of China (Grant Nos 17FZS047 and 20FZSB006) and the National Natural Science Foundation of China (Grant No. 41761037).

Acknowledgments

The authors thank the Agriculture and Rural Affairs Bureau, Poverty Alleviation Office, and Rural Revitalization Bureau of the People's Government of Diqing for their data support and full cooperation. The authors are very grateful to the editors and reviewers for their great efforts.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 30 March 2023
DOI 10.3389/fenvs.2023.1106969

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OPEN ACCESS

EDITED BY
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SPECIALTY SECTION
This article was submitted to
Environmental Economics
and Management,
a section of the journal
Frontiers in Environmental Science

RECEIVED 24 November 2022
ACCEPTED 17 March 2023
PUBLISHED 30 March 2023

CITATION
Zhang Y, Wang M and Wu K (2023), What drives willingness to travel in the context of COVID-19?—A measurement of eco-environmental values.
Front. Environ. Sci. 11:1106969.
doi: 10.3389/fenvs.2023.1106969

What drives willingness to travel in the context of COVID-19?—A measurement of eco-environmental values

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The outbreak of COVID-19 has had tremendous impacts on human health and the world economy. Studies have focused on the impact of COVID-19 on potential tourists and tourism destinations from the perspectives of individuals, industries and organizations, and they have provided some measures for tourism recovery. However, under the situation of individual restriction, research has not systematically explained residents' desire for trips of different distances and factors or the similarities and differences in the factors affecting tourism willingness for trips of different distances. In this context, a measurement of eco-environmental values is used to investigate these issues to help the tourism economy recover. Using online questionnaires covering all provinces in mainland China, this paper investigates residents' travel willingness to make trips of different distances, and it utilizes binary logistic regression analysis to examine the factors that help predict tourists' travel intentions. In addition, the patterns of willingness to travel different distances are displayed in maps generated by ArcGIS software. The results suggest that the objective COVID-19 confirmed case distribution follows distance decay theory; however, the distribution patterns of travel willingness are not in accordance with distance decay. The factors that have a significant impact on predicting travel willingness regarding the three kinds of trip distances are educational background, cognition of COVID-19, and geographical division factors. Income and the severity of the pandemic situation play different roles in predicting travel willingness in this study. Overall, the findings of this study extend the application of distance decay theory, which contributes to tourism studies in the COVID-19 context. The findings are also beneficial for tourism recovery and crisis management against the backdrop of pandemic normalization.

KEYWORDS

distance decay theory, travel willingness, eco-environmental values, spatial distribution, risk, crisis management

1 Introduction

The outbreak of COVID-19 was a major attack on human life and had unexpected negative effects on global development (Gössling et al., 2020; Yang et al., 2021a). This emerging international public health threat has caused many deaths, illnesses, and unhappiness. According to the World Bank, global GDP has suffered a 5.2% contraction due to COVID-19 (World Bank, 2021). Although governments and countries have put extraordinary efforts into recovery, recovery appears uneven across the world, and in 2022, global GDP is still estimated to remain 1.8% below pre-pandemic projections (World Bank, 2021). Moreover, the tourism industry has been severely affected by the lockdown and quarantine measures due to COVID-19 (Gössling et al., 2020; Yang et al., 2021b; Wang et al., 2021). It has been said that 2020 was the worst year on record for tourism (World Tourism Organization, 2021). According to the UNWTO World Tourism Barometer (January 2021), the number of international visitors declined by 74%, from nearly 1.5 billion in 2020 to approximately 381 million in 2019 (World Tourism Organization, 2021), which represents an estimated 1.3 trillion USD loss in international tourism expenditure. During the pandemic period, many restrictive measures have been taken in China, such as quarantine at home. This kind of restriction has strongly limited daily activities, especially travel behaviors. However, based on the forbidden fruit effect (Bushman and Stack, 1996), which states that anything that seems unobtainable becomes more desirable, this strict home quarantine increased residents' willingness to travel at the beginning of the pandemic.

Tourism demand research has shown continued growth in recent years. In previous research, scholars used social media and internet data to construct different forecasting models to predict tourism demand, especially international tourist flows, due to the high accessibility of statistical data (Song et al., 2019). Research on international tourism demand mainly focuses on predicting tourists' arrivals, tourism expenditures or length of stay (Song and Lin, 2010; Emili et al., 2020). Studies have also investigated domestic tourism flows, such as tourist arrivals in Beijing, (Li et al., 2017), hotel room demand, recreation site demand and competition forecasting (Chen et al., 2003; Song et al., 2013). Tourism demand may be influenced by various factors, and eco-environmental value is one of the most important factors impacting tourists' travel willingness (Huang et al., 2018). In this paper, eco-environmental values refer to people's views and convictions regarding COVID-19 virus knowledge and the significance of environmental protection and conservation. This concept was derived from the brief inventory of values developed by Stern et al. (1993). Stern's scale has three dimensions, i.e., social-altruistic value, egoistic value and biospheric value, and the scale is generally used to explain behaviours or behavioural intentions, especially in the pro-environmental field. This usage further suggests that there is a favorable relationship between eco-environmental values and travel readiness, as travelers who have strong eco-environmental values are more likely to give environmental factors top priority when making travel choices and are consequently more willing to partake in travel activities that are consistent with their values.

In the context of the COVID-19 pandemic, many studies have focused on tourism development. Based on the unit of analysis, studies can be divided into four different categories (Yang et al., 2021b): those focusing on individual tourists' perceived risk of traveling (Sánchez-Cañizares et al., 2021), those paying attention to organizations' operational response and financial performance (Salem et al., 2021), those examining destination-specific effects on tourism destinations and coping strategies (Yang et al., 2021a; Li X. et al., 2021) and those focusing on how the pandemic has affected the tourism industry and subindustries (Dolnicar and Zare, 2020). Moreover, COVID-19 has been a major crisis in recent years, and it has also affected residents' eco-environmental values. Whether a change in these values would have an impact on travel willingness remains unknown. Although there are many research papers related to tourism demand under this pandemic background, the patterns of tourists' travel choice intention under different distances without any specific destination have not been examined.

This paper aims to fulfil the following three objectives. 1) We examine the travel choice patterns under trips of different distances among different groups by investigating residents' willingness to engage in suburban, domestic or overseas travel. 2) We explore what the different and similar factors that affect the prediction of suburban recreation, domestic travel, or outbound travel choices are. 3) We reveal whether tourism distance choice patterns are consistent with the principles of distance decay theory. Examining these issues will help identify tourism demand in the pandemic context, support disaster resilience and tourism crisis management, and aid in tourism market forecasting against the backdrop of pandemic normalization.

2 Literature review

2.1 Distance decay theory

"Distance" is a basic concept of geography. According to Tobler's first law (Tobler, 1970), the force of an object or phenomenon decreases with increasing geographical distance. Numerous studies have confirmed the prevalence of distance decay in human spatial behaviors, and distance friction is thought to be an important cause of this phenomenon. The distance decay theory used in the tourism field indicates that tourism demand decreases when the distance increases (Smith, 1985; Zhang et al., 1999).

Distance decay exists in both objective facts and subjective tourist behaviors. Nilbe et al. (2014) investigated the distance that tourists would travel to Estonia and found that event destinations attracted event visitors from nearer locations (531 km, on average) compared to regular visitors (700 km); additionally, more than 70% of visitors were from neighboring countries. Studies have also found that some cognitive evaluations also obey distance decay theory. Xiao et al. (2021) discovered that place dependence on Jiuzhai Valley National Park decreased with increasing distance. Other scholars have also used distance decay theory to investigate the spatial correlation between provincial industrial green total-factor energy efficiencies (Chen et al., 2022). In general, distance decay exists in personal travel, which has been formalized in theoretical and practical studies (Smith, 1985). Distance has significant impacts on tourism demand, tourism intentions, and the decision-making process because travel is an activity that costs money and time (Mckercher and Lew, 2003; Nilbe et al., 2014). A distance decay pattern can be identified for tourists visiting a tourism destination, which helps segment rural tourist groups (Cai and Li, 2009) and nature-based tourism markets (Nyaupane and Graefe, 2008).

2.2 Personal factors and travel choice

Personal factors, including sociodemographic and sociopsychological features, differ among visitor groups choosing trips of different distances. A study focusing on business trips to

Hong Kong made by visitors from different distances found that the older group chose long-haul trips and mainly chose to travel on their own (Ho and McKercher, 2014). This finding is supported by other scholars, especially for distant tourism destinations. Travelers from Hong Kong prefer the independent travel type (Lee et al., 2012), and older tourists between 41 and 60 years old tend to choose longer-distance nature-based tourism destinations (Nyaupane and Graefe, 2008). In addition, the study indicated that men are more likely to choose long-haul travel than women (Ho and McKercher, 2014). Similarly, McKercher found that short-haul destinations attract more younger people, who are less educated and have lower income. In contrast, older people with high educational levels prefer to choose long-haul destinations (McKercher, 2008a). However, Collia and his colleagues (2003) analyzed the 2001 National Household Travel Survey (NHTS) to reveal the travel pattern of residents in the United States: older people were less mobile than younger people and preferred short-distance travel, and this aspect was more pronounced among older women (Collia et al., 2003). Sociopsychological features include tourists' perception, cognition, etc., a recent study on COVID-19 risk perception and travel intentions indicated that trust and strong perceptions of solidarity between people and the government have positive effects on travel intentions (Rastegar et al., 2021). Tourists' cognition of low-carbon tourism also has a significant impact on green travel mode choices (Tang et al., 2018). Additionally, environmental values and environmental cognitions have positive effects on tourists' environmentally responsible behaviors and predictive effects on pro-environmental behaviors during trips (Huang et al., 2018). In summary, environmental values have been validated to have impacts on behavior intentions. Research will investigate whether travel choice intentions (which refer to intentions towards trips of different distances without specific destinations, such as suburban recreation, domestic travel and oversea travel), which are one kind of behavioral intention, will be affected by environmental values in the context of COVID-19.

Although scholars have investigated the effects of sociodemographic characteristics and sociopsychological characteristics on travel choices, research on the effects of eco-environmental values on different kinds of distance travel intentions in the context of COVID-19 has not received enough attention. Therefore, this study will examine the differences in the willingness to travel different distances considering demographic factors and eco-environmental value variables to discover the relationships among these factors.

2.3 Scenario factors and travel choice

Crises tend to negatively affect the development of the travel industry to some extent. The different types of crises include natural crises and man-made crises, such as wars, earthquakes, and the COVID-19 pandemic. Many studies have focused on the impacts of crises on travel intentions and tourist behaviors (Pain, 2014; Zhang et al., 2021; Sasaki et al., 2022). For example, terrorism is a man-made crisis that aims to trigger widespread fear (Pain, 2014). This kind of public event is believed to have negative impacts on travel-related choices. More specifically, tourists' intentions towards the attractions affected by terrorism attacks decline significantly (McKercher and Bob, 2004; Walters et al., 2019; Sasaki et al., 2022). In addition to terrorism, COVID-19 has become a severe crisis since the outbreak of the disease at the end of 2019. COVID-19 has dramatically impacted the tourism and hospitality industry and greatly changed tourists' behaviors (Gössling et al., 2020; Wang et al., 2021; Yang et al., 2022). A case study by Porto indicated that tourists' visiting time is shorter than usual because of the pandemic and that the available visited areas are limited (Lopes et al., 2021). Due to the COVID-19 pandemic, the travel style has also changed. Scholars have concluded that Chinese travelers choose to travel independently or in small groups (Wen et al., 2020). However, scholars have noted that some disasters have no impact on tourist behaviors. Surveys in New Zealand indicated that there were very few impacts on tourists' perceptions and behavior towards earthquake-damaged attractions because of a lack of knowledge of the crisis (Fountain and Cradock-Henry, 2020).

The COVID-19 pandemic is a serious worldwide health event that poses great threats to people's tourism willingness and choice. Because this kind of virus has high spread and infection characteristics, the virus may be affected in the process of population movement and residents' willingness to travel in the context of COVID-19. In addition, in current research, many scholars have examined the impact of general crisis scenarios, such as earthquakes, wars, etc., travel choice. However, research on the impact of the scenario of the COVID-19 pandemic on travel intentions has received little attention. Therefore, we utilize COVID-19 confirmed cases to represent the severity of the pandemic crisis and examine the differences among individuals' willingness to undertake different kinds of travel, such as short-, medium-, and long-distance trips, predicted by the scenario indicator of confirmed COVID-19 cases. Additionally, we investigate whether different provinces with different COVID-19 confirmed case rates have different levels of travel choice willingness for different distances.

2.4 Travel distance and travel choice

The decision to travel might be significantly influenced by the trip distance because it is one of the most crucial aspects influencing people's decisions when selecting a method of transportation and destination (Ding et al., 2017). Travel distance is related to the travel time, cost, and convenience, and these factors can all influence travel behavior. One of the important concepts related to travel distance is perceived distance. Perceived distance refers to the estimated distance between destinations based on previous experience and knowledge (Canter and Tagg, 1975). This concept is thought to better explain tourists' behaviors (Ankomah et al., 1995). Perceived distance has been largely examined as an explanatory variable in the field of tourism destination research, and it significantly influences tourism destination image (Crompton, 1979; Zhang et al., 2011). Research on tourists' intentions towards visiting Mexico indicated that the respondents who were much farther away from Mexico had a more favorable image of Mexico City as a tourism destination (Crompton, 1979). In line with this finding, a study on the perceived image of Zhouzhuang, Suzhou, China, showed that with the increase in the origin–destination distance, tourists' perceived image recognition and cognitive destination image increased (Zhang et al., 2006). In addition, distance has an impact on travelers'

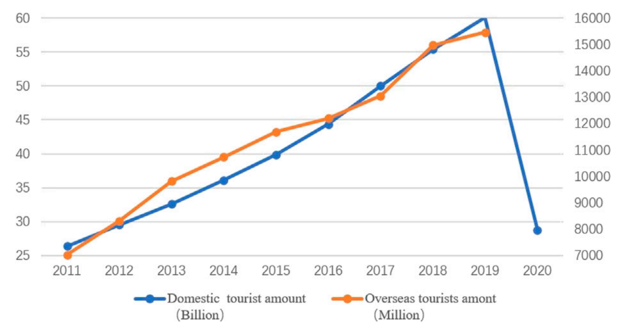

FIGURE 1
Trend of domestic and overseas travel arrivals (2011–2020).

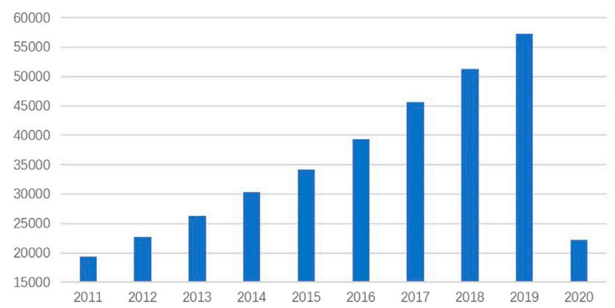

FIGURE 2
Trend of total travel expenditure 2011–2020 (billion).

satisfaction. A study conducted in Jiuzhaigou Village found that perceived distance has a positive impact on tourist satisfaction. The estimated perceived distance decreased as tourism satisfaction increased (Zhang et al., 2011).

Travel distance has been examined by many studies, and this topic can be introduced from two perspectives: the supply side and the demand side. On the one hand, travel distance can be affected by destination safety perceptions. Travel intentions are largely affected by tourists' perceptions of destination safety, which influence the decision-making process (George, 2003; Yang et al., 2019). Unsafe destinations entail decreased willingness to undertake tourism trips (Song et al., 2018). However, this decision is less associated with travel distance than with destination safety. Song et al. (2018) investigated ten young Chinese group members' travel decision-making process. They showed that a potential destination would be rejected if members were concerned about safety issues related to natural disasters or political instability (Song et al., 2018). On the other hand, from the demand side, the willingness towards different travel distances is linked to tourists' individual factors. According to the leisure constraints model (Crawford et al., 1991), structural barriers, interpersonal barriers and intrapersonal barriers constrain tourists' leisure activities. For example, structural barriers such as family financial resources, climate, the scheduling of time and other participants' related factors affect travel choice (Crawford and Godbey, 1987). Interpersonal barriers such as tourists' psychological states, perceived self-skills and subjective evaluations also affect travel willingness (Crawford et al., 1991). Furthermore, residents' living environment has an impact on travel distance choice. It has been discovered that people who live in congested areas go farther less frequently (Maat and Timmermans, 2009). Moreover, uncertainty and tourists' risk perception impact destination choices (Karl, 2018).

3 Methodology

3.1 Study site

Our study site was mainland China, including 23 provinces, 5 autonomous regions, and 4 municipalities directly under the central government. In late December 2019, Wuhan city in Hubei Province was the first to suffer from COVID-19 in China. COVID-19 spread to other regions in China with a high speed of infection. In the first month, the confirmed cases in Wuhan reached more than 45,000, and almost 2,000 people died from the disease. Based on the official administrative division and the specialty of Wuhan city, we divided our study site into five regions for geographical analysis. This kind of crisis caused significant damage to the tourism industry in China. Domestic tourist numbers declined significantly in 2020 (Figure 1). In addition, total travel expenditures in China declined due to the COVID-19 pandemic (Figure 2).

3.2 Data collection

We adopted an online questionnaire to collect data through a professional platform in China named "Wenjuanxing". We chose the snowballing method to distribute our questionnaires. First, we shared the survey with friends in various provinces, and then, they invited their friends to complete this survey. Using the convenience sampling method, this study obtained research data during the very beginning of the outbreak of the COVID-19 pandemic from January 23 to 24 February 2020, including a pre-study process. Then, we distributed 2,800 surveys and received 2,724 valid samples, for an effective response rate of 97.3%. After screening out the 3% of samples from the Hong Kong, Macau, and Taiwan areas, our study site mainly focused on mainland China, covering 34 provincial administrative regions. Because of the infectiousness of COVID-19, an online survey was the most convenient and the safest way to collect data about people's perceptions of the pandemic and travel willingness towards trips of different distances. Questions are organized into four main sections in the questionnaire. First, this survey collected the respondents' sociodemographic information, including age, gender, educational background, and monthly income. The questions in the second section asked about eco-environmental values in the COVID-19 scenario (EV-COVID), and the items were rated using 5-point Likert scales ("1" indicated that the respondent strongly agreed with the items, and "5" indicated that the respondent strongly disagreed with the items). This measurement was developed from the brief inventory of values developed by Stern et al. (1993), which includes social-altruistic value, egoistic value and biospheric value. Based on the questions in this scale, we combined the cognition of the COVID-19 pandemic with the current survey questions. Examples include "Once a person is infected with the coronavirus, it will pose a great threat to human life" and "Personal protection can help prevent viral infections".

The questions in the third section measured the respondents' travel desire in the data collection period. More specifically, the participants were asked to answer yes or no regarding their intentions towards trips of different distances, suburban recreation, domestic travel and overseas travel. In the question notes, we informed the participants that suburban recreation refers to leisure activities in public places such as parks and gardens in the countryside within a 1.5-h drive. Domestic travel refers to travel within China, and overseas travel means taking a trip abroad. Finally, we asked respondents to record their living location when completing the survey. In addition to the questionnaire, we collected the confirmed case rate to analyze the regional differences in the choice of travel distance. We collected data on confirmed COVID-19 cases from the website of the "National Health Commission of the People's Republic of China" from January 23 to 24 February 2020.

3.3 Data analysis

We used SPSS software to conduct factor analysis to divide the eco-environmental value in the COVID-19 scenario (EV-COVID) into three dimensions (Cronbach's α = 0.881). Then, we divided "the number of people who chose a specific travel type in province A″ by "the total number of participants in province A″ to calculate the proportion of suburban recreation, domestic travel, and overseas travel. This method can reduce the bias involved in using the number of participants for each type of travel. We also divide the geographical division of the whole China area into five parts according to the official administrative division and pandemic severity level. Therefore, the five divided regions are "Hubei province", "adjacent provinces of Hubei", "western regions", "eastern and southern coastal regions" and "northern regions". The layer coloring function in ArcGIS software was applied to draw the distribution of confirmed COVID-19 cases during the data collection period and the spatial distribution patterns of the three kinds of travel willingness (suburban recreation, domestic travel, and overseas travel). More specifically, based on the confirmed cases numbers throughout China, we used six layers to display pandemic severity. Because the maximum and minimum values are so far apart, they cannot be divided equally into six stages. Thus, we used the following ranges to define the six layers: 0–174, 175–399, 400–755, 756–1,345, 1,346–3,000 and above 3,000. For the distribution of the three kinds of travel willingness, we divided the proportion of each choice into five equal layers. Finally, binary logistic regression was conducted to examine the impact of sociodemographic factors (including gender, age, education level, and monthly income), the three factors of EV-COVID, and geographical division factors for predicting different distance travel choices. For each categorical factor, we set a reference group. For the geographical division factor, we set Hubei Province as a reference group because this region suffered from the pandemic most seriously at the beginning of the disaster.

4 Results

4.1 Demographic information and variable description

As shown in Table 1, the sample consisted of 55% females and 45% males. Approximately 36% of respondents were 19–24 years old. Most of the participants had college or undergraduate degrees. In addition, approximately 44% of respondents have less than 3000 RMB monthly income. The factor deduction results of eco-environmental value in the COVID-19 scenario (EV-COVID) are displayed in Table 2.

4.2 Distribution of confirmed COVID-19 cases

Figure 3 shows the distribution of confirmed cases during the survey collection time and this pattern obeys the distance decay theory. Hubei Province had the largest number of confirmed cases, as it suffered from the pandemic most severely during the collection period. The provinces adjacent to Hubei, such as Anhui Province, Henan Province, Shanxi Province, and provinces in the eastern coastal areas suffered less than Hubei. There were fewer confirmed COVID-19 cases in the western and northern regions. In summary, the confirmed cases generally decreased with increasing distance to Hubei Province.

4.3 Spatial distribution of the proportions of willingness for three kinds of travel

From the spatial distribution of the proportions of willingness for the three kinds of travel (Figure 4), it is clear that the largest number of people would choose suburban recreation (Figure 4), while the smallest number of participants would like to engage in overseas travel. This phenomenon obeys the distance decay theory; that is, as the travel distance increases, the willingness to travel decreases. More specifically, the proportion of willingness to engage in suburban recreation reached almost 73%, while the proportion of willingness to engage in overseas travel ranged only from 0% to 25%. In addition, based on the Heihe–Tengchong Line (Hu Huanyong's population demarcation line is also the social and economic demarcation line in China), the willingness distribution on the two sides of this demarcation line has different patterns. For suburban recreation, the proportion ranged from 0 to 0.1538 north of the Heihe–Tengchong Line. However, 15.39%–72.87% of residents who would like to choose this kind of recreation were distributed south of the Heihe–Tengchong Line. For domestic travel, proportions lower than 12.95% were distributed north of the Heihe–Tengchong Line, and proportions higher than 12.96% were distributed in the southern part. Similarly, for overseas travel, people in the southern part had high willingness. Guangdong Province had the highest proportion for each type of travel.

4.4 Predicting the choice of travel distance

4.4.1 Predicting the choice of suburban recreation

Gender has significant impacts on predicting the willingness to choose suburban recreation. The reference category for the gender variable was female (Table 3). The value of Exp(B) was 1.181, which means that men were 1.181 times more likely than women to choose suburban recreation activities. Age also had a significant impact on predicting the choice of suburban recreational activity ($p < 0.1$). Educational background was

TABLE 1 Respondent demographic characteristics.

	Item	Frequency	Percentage (%)
Gender	Male	1,232	45.23
	Female	1,492	54.77
Age	<18 years old	235	8.63
	19–24 years old	974	35.76
	25–34 years old	408	14.98
	35–44 years old	436	16.01
	45–54 years old	414	15.20
	55–64 years old	157	5.76
	>65 years old	100	3.67
Education level	High school or below	628	23.05
	College or undergraduate	1,638	60.13
	Master degree	259	9.51
	postgraduate	199	7.31
Monthly income	<3000 RMB	1,195	43.87
	3,001–5,000	447	16.41
	5,001–10000	471	17.29
	10,001–15000	376	13.80
	15,001–20000	111	4.07
	20,001–30000	83	3.05
	>30,001	41	1.51
Suburban recreation	Yes	773	28.4
	No	1951	71.6
Domestic travel	Yes	589	21.6
	No	2,135	78.4
Overseas travel	Yes	316	11.6
	No	2,408	88.4

also a significant predictor ($p < 0.01$). The categories in the table compared to the reference group (high school, secondary school, or lower) are all significant, and they have negative coefficient values of −0.437, −0.550, and −1.100, respectively. That is, all the groups with an educational background above high school were less likely to choose suburban recreation as their preferred activity than the reference group. For the three factors of EV-COVID, only cognition of COVID-19 had a significant impact on predicting whether people would choose suburban recreation ($p < 0.01$), and the coefficient of this item was a positive value. However, the confirmed COVID-19 case rate was not a significant predictor. Moreover, the division of regions in China had a significant impact on predicting the choice of suburban recreation ($p < 0.01$). The results show that people in the other four parts of China, namely, in the northern regions, provinces adjacent to Hubei, western regions, and eastern and southern coastal regions, had a significantly higher willingness to choose suburban recreation than people in Hubei Province.

4.4.2 Predicting the choice of travel domestically

Age ($p = 0.043$) and educational background ($p < 0.05$) are significant predictors of whether people choose domestic travel (Table 4). In the educational background category, the coefficient of the master's degree group is a negative value (B = −0.719). The Exp (B) value of this item is 0.487, which means that people with master's degrees are 0.487 times less likely than the reference group of people to choose domestic travel. People with an undergraduate degree were also less likely than the reference group to choose this kind of tourism activity. Monthly income had no significant impact ($p = 0.425$). Moreover, similar to the impact on suburban recreation, the cognition of the COVID-19 factor had a significant impact on predicting whether tourists chose domestic travel. In addition, the p-value of the factor of the confirmed COVID-19 case rate was

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TABLE 2 EV-COVID factor analysis results.

Dimension	Items	Cronbach's α
Cognition of COVID-19	COVID-19 virus is highly contagious	0.825
	COVID-19 virus has widespread channels	
	No effective drugs are available for this virus	
	It will pose a great risk to human life if infected	
	Personal protection can largely help prevent viral infections	
Cognition of the relationship between human and nature	Humans are wreaking havoc on wildlife	0.829
	Human will continue to suffer "plague disasters"	
	Nature destruction by human would lead to catastrophic consequences	
	The balance of nature is fragile and can easily be disturbed	
	Animals have the same right to live as humans	
	Humans need to respect wildlife although they have the ability to exploit nature	
	Technology and human intelligence and eventually defeat all kinds of viruses	
Anthropocentrism	The so-called "pandemic crisis" is an overstatement	0.721
	Human beings have the right to use or eat any wild animal for their own needs	
	Humans are supposed to be the rulers of the natural world	

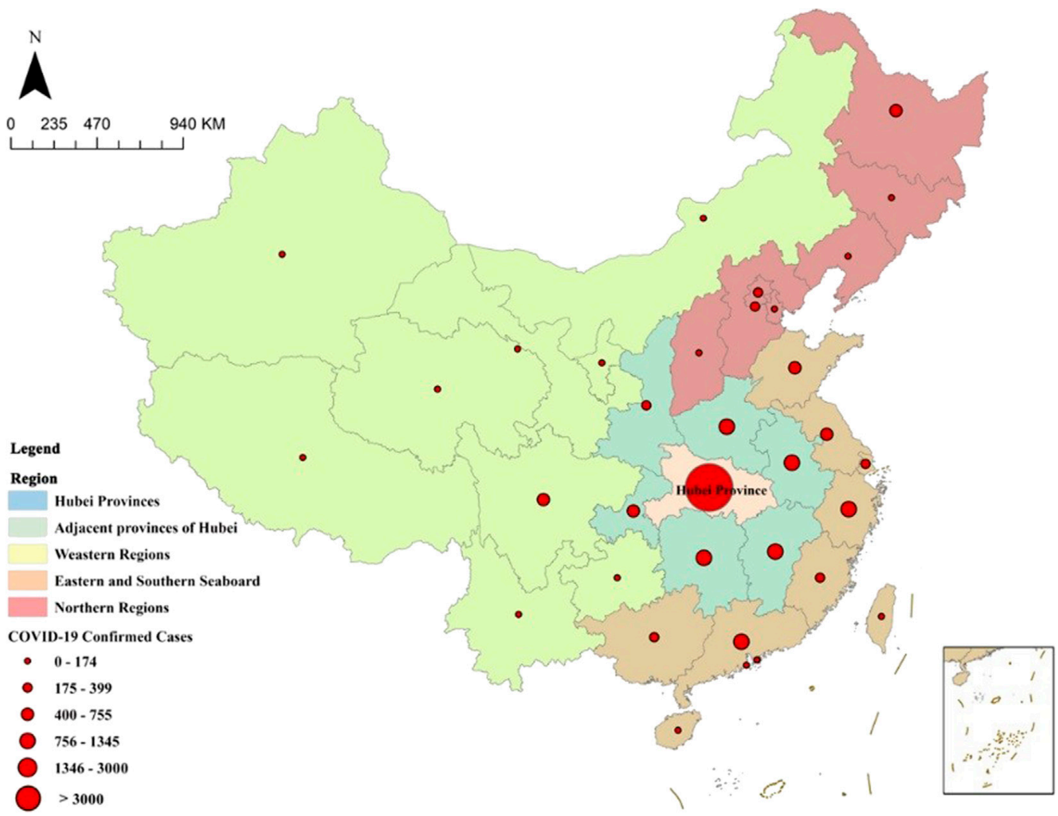
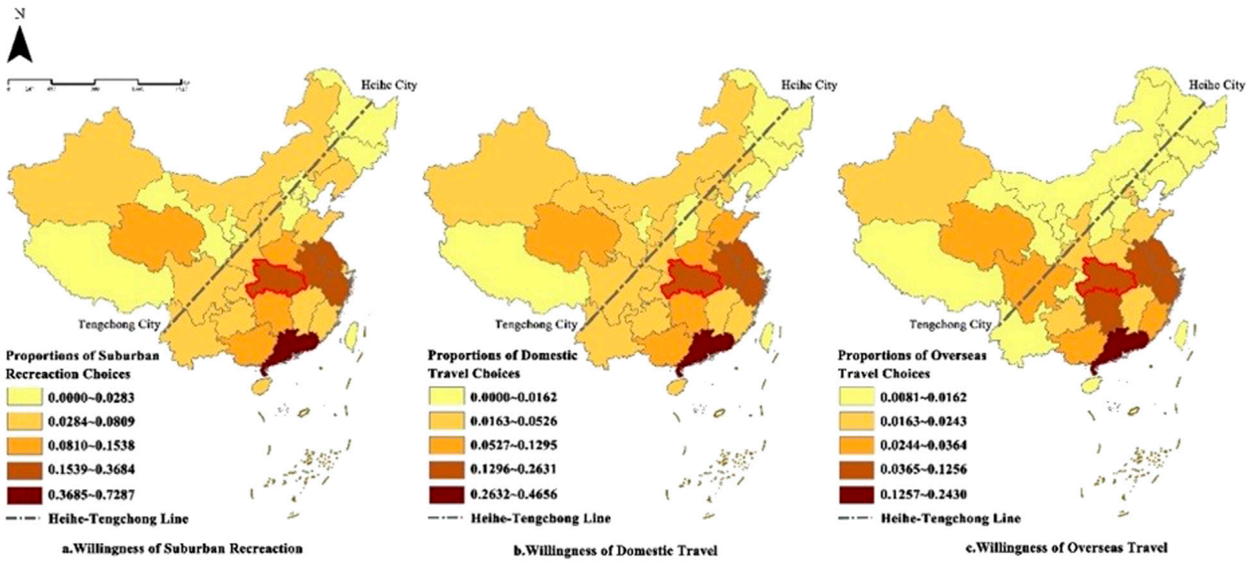


FIGURE 3
Distribution of confrimed COVID-19 cases.



Note: The proportion is calculated by "The number of people who chose a specific travel type in province A" / "the total number of participants in province A".

FIGURE 4
Spatial distribution of three kinds of travel willingness proportion.

TABLE 3 Predicting the choice to suburban recreation.

	Suburban recreation					
	B	SE	Wald	df	Sig	Exp(B)
Gender			3.227	1	0.072*	
Male	0.166	0.093	3.227	1	0.072*	1.181
References group: Female						
Age	−0.06	0.036	2.803	1	0.094*	0.942
Education background			30.989	3	0.000***	
PhD degree	−0.437	0.207	4.469	1	0.035**	0.646
Master degree	−0.550	0.172	10.274	1	0.001***	0.577
Undergraduate degree (or junior college)	−1.100	0.205	28.899	1	0.000***	0.333
References group: high school, secondary school or lower						
Monthly income	−0.015	0.035	0.187	1	0.666	0.985
Cognition of COVID-19	0.526	0.094	31.059	1	0.000***	1.692
Cognition of the relationship between human and nature	0.029	0.095	0.090	1	0.764	1.029
Anthropocentrism	0.082	0.059	1.949	1	0.163	1.086
confirmed COVID-19 cases rate	0.000	0.000	1.153	1	0.283	1.000
Division of regions			24.747	4	0.000***	
Northern regions	0.695	0.199	12.150	1	0.000***	2.003
Adjacent provinces of Hubei	0.617	0.208	8.829	1	0.003**	1.854
Western regions	0.900	0.190	22.503	1	0.000***	2.459

(Continued on following page)

TABLE 3 (*Continued*) Predicting the choice to suburban recreation.

	Suburban recreation					
Eastern and southern seaboard	0.835	0.267	9.782	1	0.002**	2.305
References group: Hubei province						
Constant	−3.585	0.472	57.796	1	0.000***	0.028
Cox and Snell R Square	0.078					
Nagelkerke R Square	0.112					
Hosmer and Lemeshow Test	22.423					

$^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.

TABLE 4 Predicting the choice to domestic travel.

	Domestic travel					
	B	SE	Wald	df	Sig	Exp(B)
Gender			0.077	1	0.782	
Male	0.028	0.101	0.077	1	0.782	1.028
References group: Female						
Age	−0.081	0.040	4.108	1	0.043**	0.922
Education background			38.498	3	0.000***	
PhD degree	−0.196	0.213	0.845	1	0.358	0.822
Master degree	−0.719	0.181	15.780	1	0.000***	0.487
Undergraduate degree (or junior college)	−1.156	0.219	27.851	1	0.000***	0.315
References group: High school, secondary school or lower						
Monthly income	−0.031	0.039	0.636	1	0.425	0.97
Cognition of COVID-19	0.382	0.101	14.249	1	0.000***	1.466
Cognition of the relationship between human and nature	0.107	0.103	1.060	1	0.303	1.112
Anthropocentrism	0.090	0.065	1.950	1	0.163	1.094
confirmed COVID-19 cases rate	0.000	0.000	3.356	1	0.067*	1.000
Division of regions			21.814	4	0.000***	
Northern regions	0.583	0.216	7.273	1	0.007**	1.792
Adjacent provinces of Hubei	0.397	0.228	3.034	1	0.082*	1.487
Western regions	0.724	0.206	12.377	1	0.000***	2.062
Eastern and southern seaboard	1.109	0.277	16.049	1	0.000***	3.032
References group: Hubei province						
Constant	−3.289	0.506	42.255	1	0.000***	0.037
Cox and Snell R Square	0.058					
Nagelkerke R Square	0.09					
Hosmer and Lemeshow Test	15.389					

$^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.

0.067, which was less than 0.1. This item is a significant predictor. The results indicate that the division of regions in China is also a significant predictor for the choice of domestic travel. Among the four compared groups, compared to people in the other three regions, people in the eastern and southern coastal regions had the highest willingness to engage in domestic travel. More

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TABLE 5 Predicting the choice to overseas travel.

	Overseas travel					
	B	SE	Wald	df	Sig	Exp(B)
Gender			3.648	1	0.056*	
Male	0.246	0.129	3.648	1	0.056*	1.278
References group: Female						
Age	−0.051	0.048	1.104	1	0.293	0.951
Education background			7.157	3	0.067*	
PhD degree	0.228	0.273	0.702	1	0.402	1.257
Master degree	0.012	0.234	0.002	1	0.960	1.012
Undergraduate degree (or junior college)	−0.407	0.282	2.085	1	0.149	0.666
References group: High school, secondary school or lower						
Monthly income	0.165	0.045	13.618	1	0.000***	1.179
Cognition of COVID-19	0.402	0.129	9.673	1	0.002**	1.494
Cognition of the relationship between human and nature	−0.090	0.129	0.488	1	0.485	0.914
Anthropocentrism	−0.118	0.078	2.294	1	0.130	0.889
confirmed COVID-19 cases rate	0.000	0.000	1.314	1	0.252	1.000
Division of regions			10.459	4	0.033**	
Northern regions	0.009	0.251	0.001	1	0.971	1.009
Adjacent provinces of Hubei	0.026	0.263	0.010	1	0.921	1.026
Western regions	0.33	0.23	2.051	1	0.152	1.390
Eastern and southern seaboard	0.703	0.318	4.874	1	0.027**	2.020
References group: Hubei province						
Constant	−3.439	0.603	32.551	1	0.000***	0.032
Cox and Snell R Square	0.024					
Nagelkerke R Square	0.046					
Hosmer and Lemeshow Test	11.309					

*$p < 0.1$; **$p < 0.05$; ***$p < 0.01$.

specifically, people in these regions were approximately 3 times more willing than people in the Hubei region to travel domestically.

4.4.3 Predicting the choice of travel overseas

Gender has a significant impact on predicting the willingness to travel overseas (Table 5). Similar to the other two types of travel, educational background is also a significant factor. However, unlike the other two types of travel, monthly income has a significant impact on predicting whether people choose overseas travel. The coefficient value is 0.165, which means that people are more likely to choose the overseas travel type when they have a higher monthly income. In addition, the *p*-value of the cognitive value of the COVID-19 factor is 0.002, which is less than 0.1. Moreover, cognition of the relationship between humans and nature, anthropocentrism, and confirmed COVID-19 case rate factors have no significant impact. In addition, the odds of choosing overseas travel are approximately 2 times higher for people in the eastern coastal region than for people in Hubei Province (p = 0.027).

5 Discussion and conclusion

This study has identified the objective fact that COVID-19 confirmed cases decreased with increasing distance from Wuhan city, which obeys the distance decay theory pattern. However, the travel willingness for trips of different distances did not follow the distance decay theory. By applying quantitative methods to examine the personal characteristics, situational and location factors that predict the willingness to make choices regarding three different travel distances—suburban recreation, domestic travel, and overseas travel—the study has also shown that similar factors for predicting the willingness to make trips of three kinds of travel distances are educational background, cognition of COVID-19, and geographical division. However, income, gender and confirmed cases of COVID-19 play different roles in prediction.

5.1 Theoretical implication

5.1.1 The spatial distribution of confirmed COVID-19 cases obeys distance decay theory

Most COVID-19 confirmed cases occurred in Wuhan city, and the number of confirmed cases decreased as the distance to Wuhan city increased, which obeys the distance decay theory (Taylor, 1971). Because of the highly contagious and widespread features of the coronavirus, people are more easily infected by this kind of disease *via* contact with pathogens (Chen et al., 2020). In addition, the very beginning of the COVID-19 outbreak in Wuhan city coincided with the Chinese New Year, during which time people's movement increased significantly across China. The large floating population and convenient transportation system in Wuhan cause a high frequency of contact with people, goods, and transportation in close proximity to Wuhan and therefore a high probability of being infected (Ning et al., 2021). However, with the tremendous efforts of the Chinese government, policies on mandatory mobility restrictions and health and safety defences, such as lockdown and home quarantine measures, largely controlled the spread of the disease. Therefore, the distribution of confirmed cases decreased from the point of Wuhan city. This was also validated in other studies in which the spread of COVID-19 followed Tobler's first law of geography, showing a proximity spreading pattern (Wang et al., 2020). Our results are consistent with many facts that obey the rules of distance decay theory. For example, the manufacturing industry in China is highly concentrated in developed coastal cities, such as those in the Pearl River Delta, Yangtze River Delta, and Bohai Rim regions. In addition, with the increase in distance from developed coastal cities, the number of industries gradually decreases (He et al., 2007).

5.1.2 Travel willingness disobeys the distance decay theory

For travel choice willingness regarding the three different distances in China, this pattern does not represent the highest willingness in Wuhan city, the region most seriously affected by COVID-19 in China. With the widespread nature of this disease, the strictest restrictions were implemented in Wuhan. Therefore, residents in this region faced restrictions regarding contact with others and population movements. According to the forbidden fruit effect, potential tourists in Wuhan would have the greatest desire to go outside for outdoor and travel activities. However, people who have a high willingness to choose suburban recreation, domestic travel, and overseas travel are almost fully distributed in the southern areas of the Heihe–Tengchong Line, instead of concentrating on Wuhan city.

From the perspective of distance decay theory, our research results of travel intention patterns that do not match the distance decay are in accordance with some previous psychosocial research findings. For example, a nationwide survey was conducted on the psychological state of the population to explore the mental health status and spatial patterns of different regions and groups of the public during the pandemic (Su et al., 2020). The results indicated that at the regional level, the 31 provinces and regions show an overall spatial distribution pattern of a low sense of tension in the northeast and a high level of state tension in the southwest (Su et al., 2020). This suggested that geographical distance from Hubei Province is not a solid factor that significantly influences people's psychological situation, probably because the rapid development of the transportation network has caused the spatial sense of competent cognition to compress the spatial proximity effect under geographical distance. However, our results are not consistent with those of other studies (Xiao et al., 2021). Xiao et al. (2021) found that the relationship among visitors' place dependence, place identity, and spatial proximity follow the distance decay rule, and visitors' sense of place dependence and place identity decreases with increasing distance from Jiuzhai Valley National Park.

From the other perspective of spatial clustering, it can be concluded that the high values of the proportions of willingness to engage in the three travel types among potential tourists in China are all distributed south of the Heihe–Tengchong Line. There are two different reasons for this phenomenon. On the one hand, the confirmed COVID-19 cases show a core-periphery structure, and the regions south of the Heihe–Tengchong line include the "core" area, Hubei Province. People who have high restrictions have a high willingness to make trips. On the other hand, the data in this study were collected at the beginning of the pandemic period and most people wanted to escape from the place where they lived to avoid serious pandemic effects. Our results of travel willingness patterns can be verified from previous studies. People in Guangzhou, Jiangsu, and Zhejiang Provinces have a high willingness to travel overseas. This aligns with earlier research showing that the Yangtze River Delta cluster and the Pearl River Delta cluster consisted of hotspot areas of inbound tourist arrivals in 1999 and 2006 (Yang and Wong, 2013). Shanghai and Guangzhou are major gateway cities; therefore, they have high accessibility to inbound tourists. Similarly, the convenient transportation system of the Pearl River Delta and Yangtze River Delta clusters facilitates residents' high willingness for suburban recreation, domestic travel, and overseas travel. In addition, the study pointed out that richer individuals have higher domestic tourism demand; moreover, for urban residents in the eastern regions, the income factor plays a more important role in determining domestic tourism demand (Yang et al., 2014). Residents in the eastern part of China have an average income higher than that of residents in other regions, which can explain the phenomenon that people in eastern and southeastern China have a high willingness to travel different distances.

5.1.3 The role of personal characteristics, scenario factors and location in predicting travel willingness

The factors of education level, cognition of COVID-19, and geographical division all have significant impacts on predicting the choice of the three kinds of travel distances. The age factor had significantly negative impacts on predicting the choices of suburban recreation, domestic travel, and overseas travel. That is, older residents have a low willingness to choose outside activities. The older group of people has a higher perception of travel distance than other groups of people (Cao et al., 2019; Cao et al., 2020). Regarding geographical division factors, the eastern and southern coastal areas of China have significant effects on predicting the choice of all three kinds of travel distances and have the highest possibility times compared to Hubei Province. In particular, among these four geographical regions, only the eastern part of China has two times more willingness to travel overseas than Hubei Province. This has been verified in a previous study; residents in the coastal area of China have more options to access their preferred destinations, and they have a higher willingness than people in the inland areas of China (He, 2011). Educational background was also a significant factor for predicting the choice of the three kinds of travel distance. It is predicted that people with lower education would have higher possibilities of choosing outside travel activities. Because highly educated residents have a relatively high level of social responsibility (Crowther and Vilke, 2018), they have a high awareness of keeping rules. Therefore, instead of travelling, they would prefer to stay at home to prevent the spread of the disease. However, people with lower educational backgrounds have lower awareness of social responsibility and higher willingness to travel. The income factor has significant effects only on predicting the choice of overseas travel. In addition, people with high income have a high possibility of choosing to travel abroad, which is also in accordance with a previous study (McKercher, 2008b). It is generally believed that travelling abroad costs more than domestic and suburban travel. At the beginning of the COVID-19 pandemic in China, people who could afford the cost of overseas travel would choose this kind of trip to avoid the serious effects of the pandemic. Moreover, men prefer overseas travel more than women do, which aligns with the study conducted by Ho and McKercher (2014). However, for the domestic choice, there were no significant differences between men and women.

The factor of EV-COVID–cognition of COVID-19—has significant impacts on predicting the three kinds of travel distances. As the value of “cognition of COVID-19” increases, the possibility of choosing the three kinds of travel distance increases. We conducted some online interviews with participants to understand the reasons. The interview results showed that many people have the habit of relaxing *via* suburban recreation. They were willing to engage in this kind of travel at the beginning of the pandemic even though there were high risks. Most people also held the opinion that it was safe to make good preventive strategies when traveling outside. In addition, when the value of the “cognition of COVID-19” factor increased by one unit, the possibility of choosing overseas travel increased the most. At the beginning of the pandemic in China, the COVID-19 situation abroad was better than that on the mainland. People wanted to escape from their homes to avoid the pandemic. Previous studies have also revealed that self-value and attitudes play a significant role in tourists’ decision-making process (Huang et al., 2018; Balaji et al., 2019; Li W. et al., 2021). In studies that examined tourists’ intention and willingness to choose green hotels during their trips and to pay a premium for this kind of hotel, personal norms have been found to strengthen green hotel attribute perceptions (Balaji et al., 2019), and attitudes towards green hotels have been found to have a positive impact on purchase intentions (Yadav et al., 2018; Balaji et al., 2019). In addition, research has investigated whether past experiences and place identity, including self-value, have significant effects on travelers’ decisions (Li W. et al., 2021).

5.2 Practical implications

Our study deepens the understanding of the impacts of personal characteristics, situational factors, and geographical division factors on predicting residents’ willingness to travel different distances in the context of an unexpected health crisis. The findings of this study provide practical recommendations for the recovery of recreation and tourism activities. First, this study provides a factual basis for the government to guide tourists’ travel choices under different distances. Against the backdrop of pandemic normalization, because of the high spread ability of virus, residents need to reduce their large-scale gatherings. The distribution of the three kinds of travel willingness showed that the highest preference was for suburban recreation. Tourism departments can develop more recreational activities in suburban areas, such as camping. Second, from the travel safety perspective, managers can make rules to encourage suburban recreation activities. Third, as mentioned in the results, the value of understanding COVID-19 has effects on predicting travel types. Therefore, it is necessary to enhance the public’s awareness of pandemic severity and educate people regarding the importance of self-protection from the virus. For the next emergency crisis recommendation, a rigorous and precise prevention and control mode at the very beginning of crises is adaptive in China. More specifically, the results of this paper indicate that cognition of COVID-19 has significant impacts on travel choice intentions, which has some crucial implications for public awareness and education work. Considering residents’ health problems, it is better to enhance residents’ cognition of crises so that they make sensible travel choices. Finally, the results of this study provide some implications for tourism market forecasting for when we finally overcome the COVID-19 period.

5.3 Limitation

The main limitation of this study lies in the sample representation because of the snowballing collection method. The participants mainly consisted of college students, who are young, have a high educational level and have a low income. Further research needs to pay more attention to the percentages of different participants. Additionally, it needs to more closely examine the links between the system of value and travel willingness to further understand tourists' psychology and behaviours, which would be more beneficial for tourism development against the backdrop of pandemic normalization. Moreover, further research might explore residents' actual travel choices to compare the differences between intentions and actual behaviors, which would be more beneficial for tourism development in the tourism recovery period.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

YZ and MW have the same contributions, KW is in charge of software and validation. KW contributed to formal analysis and supervision to the contributions.

Funding

This work was supported by the National Natural Science Foundation of China (42171242); High-level Talents and Lingnan Scholars' Research Start-up Project of Foshan University (CGZ07001).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 03 April 2023
DOI 10.3389/fenvs.2023.1090853

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OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Environmental Economics and Management, a section of the journal Frontiers in Environmental Science

RECEIVED 06 November 2022
ACCEPTED 20 March 2023
PUBLISHED 03 April 2023

CITATION
Tao S, Hai M, Fang Z and Zheng D (2023), The role of environmental justice reform in corporate green transformation: Evidence from the establishment of China's environmental courts.
Front. Environ. Sci. 11:1090853.
doi: 10.3389/fenvs.2023.1090853

The role of environmental justice reform in corporate green transformation: Evidence from the establishment of China's environmental courts

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Purpose: The establishment of environmental courts in China provides a good opportunity to explores the economic effects of environmental justice reform. This paper investigates how the environmental justice reform can influence corporate green transformation from the perspective of green technology innovation and explores the potential mechanisms of how the environmental courts affect green technology innovation. The heterogeneous effects of environmental courts are also considered.

Methodology: Using the establishment of environmental courts in China as a quasi-natural experiment, this paper adopts a difference-in-difference (DID) method to conduct empirical test based on data on Chinese listed A-shared firms from 2004 to 2019. Moreover, this paper use propensity score matching (PSM), tobit and negative binomial regression method to address possible estimation bias.

Findings: The establishment of environmental courts significantly enhances green technology innovation among enterprises. The more effective judicial enforcement and better public awareness of the environment brought by the environmental courts will increase the cost of illegality and external supervision pressure for firms, which will lead firms to innovate in green technology. Furthermore, the positive and significant effect of environmental courts on green technology innovation is more pronounced in state-owned enterprises (SOEs) and enterprises located in regions where local protectionism is more serious or regions with more ideal environmental legal system.

KEYWORDS

environmental court, environmental litigation, public supervision pressure, difference-in-difference method, green technology innovation

1 Introduction

Along with the rapid industrial and urban developments in China, environmental problems have gradually become major constraints that hinder its sustainable development. According to the Bulletin of China's Ecological Environment in 2016, only 99 out of 338 cities at the prefecture level and above met environmental air quality standards, and 32.3% of surface water and 60.1% of groundwater are classified as class IV or below which refer to the water polluted or not suitable for human consumption[1]. Serious environmental degradation caused heavy burdens and losses to

1 The relevant information and data can be accessed at https://www.mee.gov.cn/hjzl/sthjzk/

China's social development and economic production (Zhou et al., 2021). In response to the economic and environmental challenges, the Chinese government has issued multiple policies and regulations, such as Emission Trading System and adoption of New Ambient Air Quality Standards in China, to achieve an environmentally friendly development model (Du and Li, 2020; Peng et al., 2021; Zhang et al., 2022). In this context, as the main body of environmental pollution in the process of industrialization, the traditional production mode of enterprises bears considerable responsibility for environmental pollution, and its green transformation is imperative. The essential factor of enterprise green transformation is green technology innovation.

Green technology innovation is regarded as an effective way to solve the contradiction between environmental degradation and economic development (Rennings, 2000; Wang et al., 2021). And it refers to the creation and adoption of new industrial production technologies and systems that contribute to pollution abatement, resource utilization, and energy efficiency rather than traditional environmentally neutral innovation (Kammerer, 2009; Cai et al., 2020; Ma et al., 2022). Through green technology innovation, enterprises can reduce the negative impact on the environment and balance economic production and environmental protection (Ghisetti and Quatraro, 2017; Li et al., 2018; Yang et al., 2021). Inducing green technology innovation in enterprises and improving green production efficiency has received extensive attention from the government and academia.

Presently, scholars mainly focus on the impact of environmental policies and regulations on green technology innovation and how these measures accelerate the green transformation of the industry (Stoever and Weche, 2018; Tao et al., 2021). However, they ignore that environmental justice may also play an important role in green technology innovation. In recent years, environmental judicial reform is attracting more attention from the Chinese government and society. Statistics show that since 2005, the disputes over environmental issues have increased by more than 30% annually (Fan et al., 2019). However, under the traditional judicial system in China, due to the public goods attributes of environmental pollution, judgments in environmental cases are often controversial because of their complexity, which tends to cause unnecessary loss of the environment and social resources. Therefore, pollution disputes involving enterprises often cannot be reasonably resolved due to the lack of environmental judicial capacity, which is not conducive to the green development of enterprises. It can be seen that environmental justice not only plays a role in protecting the environment but also has an impact on social production. In addition, a sound environmental judicial system can also guarantee the implementation and applicability of environmental policies (Liang and Gao, 2014).

In China, judicial reform and improvement represented by environmental courts are one of the government's important environmental governance measures. China's first exploration of judicial reform began in 2007. To resolve local pollution disputes, the government established the first environmental court in the Intermediate People's Court (IPC) of Qing Zhen City, Guizhou Province, in 2007. In December of the same year, the Qingzhen Environmental Court rendered its verdict public on the Tianfeng Chemical Factory case, the first public interest environmental litigation in China. Since then, the local environment there has been effectively improved.

The win-win situation of environmental protection and economic development is the ultimate goal of environmental judicial reform. After effectively eliminating the negative externalities of enterprises to the environment, a question worth further exploration is whether environmental courts will have any impact on the production behavior of enterprises, is the impact positive or negative? As green technology innovation is a key factor for enterprises to realize green and sustainable development, it has great theoretical and practical significance to explore the relationship between environmental courts and green technology innovation.

To better identify the causal effect of environmental justice reform on green technology innovation, we take the establishment of environmental courts as a quasi-natural experiment and adopt the DID approach to investigate the real impact of environmental courts on corporate green technology innovation. DID is an econometric method in a quasi-experimental design form commonly used by economists to evaluate the economic effects of shocks from policy or other unexpected events (Fang et al., 2022). Through data from the treatment and control groups, we can use the DID model to construct appropriate counterfactuals to estimate the true causal effect after the shock occurred, that is, to compare the change over time in outcomes between a group affected by the shock (the treated group) and a group that is not (the control group). On this basis, we also consider the potential mechanisms of how the environmental courts affect green technology innovation. Relying on a mediating effect model, we shed light on the potential mechanisms from perspectives of environmental litigation risk and public awareness. Furthermore, we explored the heterogeneous effects conditional on local law environment, government intervention, and firms' ownership to gain a more comprehensive understanding of the impact of environmental courts on green technology innovation. In addition, we performed a series of robustness checks to verify the validity of the results.

The contribution of our paper lies in the following aspects. First, we contribute to the literature on drivers for green transformation (Chen, 2008; Li and Sheng., 2018). Previous studies overwhelmingly focus on the impacts of environmental regulation on green innovation (Lanoie et al., 2008; Ambec et al., 2020; Fang et al., 2022), with the absence of consideration for the environmental judicial system. Our paper fills a literature gap by researching judicial factors that drive green technology innovation and highlights the critical role played by an environmental court. Our paper provided new empirical evidence that environmental courts can significantly enhance corporate green technology innovation. Second, for the stream of relevant literature on environmental justice, scholars have concentrated on the relationship between the environmental court and pollution abatement or firms' business behaviors (Zhang et al., 2019; Huang et al., 2022). Our paper not only enriches this stream of literature by focusing on green technology innovation using firm-level data but also reveals the underlying mechanisms of how environmental courts affect green technology innovation, which enables us to provide targeted policy recommendations concerning both the environment and firm green transformation.

The rest of this paper is arranged as follows. Section 2 presents the literature review. Section 3 introduces the institutional background and theoretical analysis. Section 4 introduces the econometric methodology and describes the data. Section 5 shows the benchmark analysis of the green technology innovation effect of environmental courts. Section 6 explore the underlying mechanisms. Section 7 presents the results of further analysis. And the final section concludes.

2 Literature review

In the field of environmental economics, the relationship between environmental regulation and green technology innovation has always been a perennial topic attracting scholars. Porter and Van der Linde (1995) emphasized that moderate environmental regulation can guide the direction of technological advancement of enterprises and enhance their green technology innovation ability, so as to gain competitive advantages, which is also the famous "Porter Hypothesis." In the long run, green innovation can bring stable earnings to enterprises and compensate for the cost caused by environmental regulations, thus improving productivity. Mohr and Saha (2008) derive results consistent with the "Porter Hypothesis" through a general equilibrium framework. They point out that environmental regulation may encourage enterprises to invest in green technologies, which is conducive to exploiting firms' capacity to innovate. Fang et al. (2022) reported similar findings. They study the impact of the New Environmental Protection Law (NEPL) in China and find NEPL brings supervision pressure to heavily polluting firms, prompting them to improve the quality of information disclosure, thus improving green innovation. "Porter Hypothesis" is not always valid. Due to the heavy pressure of pollution abatement cost brought by environmental regulation, enterprises may be unable to support more environmental R&D investment, thus hindering the green transformation of enterprises. For example, Stoever and Weche (2018) used the Difference-in-difference model to investigate the impact of Germany's water environmental protection policy on firms' competitiveness. In this regard, they found that the policy inhibited enterprise performance and investments in environmental protection, which is not conducive to their green development. Fan et al. (2021) suggest that environmental regulation will force enterprises to invest more in environmental protection equipment and pollution treatment costs, which will crowd out productive investment to a certain extent, making it unfavorable to urban green development in China. In addition, scholars have found that there may be a non-linear relationship between environmental regulation and green innovation. Domazlicky and Weber (2004) studied the pulp, paper and chemical industries in the United States and found that the impact of environmental regulation on innovation efficiency was uncertain in different industries. And environmental regulation may not only lead to potential output losses, but may also reduce pollution while increasing output. Li and Du (2021) examined the spatial spillover effect of environmental regulations on green innovation efficiency based on Chinese city-level data. The results show that significant spillover effects of environmental regulations on urban green innovation efficiency are reflected in a U-shaped impact that was first suppressed and then promoted.

The above literature explored the effects of government environmental governance on technical innovation from the perspectives of environmental policies and environmental supervision, but they ignored the impact of environmental justice. As a representative measure of environmental judicial reform, Environmental courts have proven to be an effective way to resolve environmental disputes and litigation (Jacobs, 2006; Almer and Goeschl, 2010). Pearlman (2000) described the Land and Environment Court of New South Wales in Australia, he gave various examples in key areas such as environmental prosecution, public participation in environmental protection and decision-making, and transboundary pollution to demonstrate the value of specialist judges and the role of environmental courts in the evolution of case law in environmental jurisprudence. Yu (2017) state that the environmental courts in China take four forms: Environmental protection tribunal, Collegial panel for environmental protection, Circuit court for environmental protection, and Courts for grassroots environmental protection. He also pointed out that China's environmental courts still have some shortcomings, such as a lack of institutional structure and professional judges. In addition, some scholars also studied the economic effect of environmental courts. Zhang et al. (2019) evaluate the effects of environmental justice reform on environmental governance at the firm level and find environmental courts significantly enhance the firms' environmental investment. Huang et al. (2022) investigate the relationship between environmental courts and foreign direct investments. They find the foreign direct investments of cities with environmental courts would drop by 3.32% from the average, which is consistent with the "Pollution Heaven Hypothesis."

Although the research findings on exploring the relationship between environmental regulation and green technology innovation are relatively abundant, there is a lack of systematic examination from the perspective of environmental justice reform represented by environmental courts. A sound environmental judicial system should not only contribute to the implementation of environmental laws and regulations but also provide positive guidance to the production behavior of enterprises. Therefore, our paper aims to add new empirical evidence on the impact of environmental justice reform on promoting green technology innovation.

3 Institutional background and theoretical analysis

3.1 Institutional background

Since the promulgation of the "Environmental Protection Law of the People's Republic of China" in 1989, the central and local legislative departments have passed hundreds of laws and regulations (Liu and Chen, 2016) to promote the existence of laws to be abide by. However, in the face of environmental violations, the public and no-profit organizations lack appropriate litigation channels, and the trial results of environmental disputes are often controversial due to the complexity of environmental issues. It can be seen that although the legal system has gradually improved, the environmental judicial processing capacity that matches it does not match.

On the one hand, under the traditional Chinese legal system, environmental cases have long been governed by three traditional categories of criminal, civil, and administrative cases according to their specific circumstances. Due to the typical negative externality and public goods attributes of environmental pollution, it is often difficult to have a unified standard and punishment intensity for the treatment of environmental cases in the traditional judicial system. At the same time, the investigation and evidence collection process of environmental protection cases have higher requirements on the professional background of the adjudicators, and the judges under the traditional court system mostly hear ordinary criminal, civil or administrative cases, which inevitably improperly grasp the application of the law when trying environmental resource cases, resulting in errors and affecting the fairness of environmental cases (Wang, 2014; Wang and Feng, 2014).

On the other hand, the public's environmental awareness and demand for environmental protection are increasing by the day. Environmental disputes in China have increased by more than 20 percent a year since 1998, but China's traditional legal system has failed to provide adequate legal protection for public or non-profit organizations. Under the traditional judicial system, environmental cases are difficult to be characterized, people often struggle to find appropriate division to initiate litigation. Even with successful appeals, environmental cases are usually linked to public interests because of the public goods attributes of the environment, so it is difficult to clearly define the legal rights and interests related to the appeal, thus forming effective support for environmental protection. As a result, the traditional judicial system is to some extent no longer applicable in solving environmental litigation.

To solve the dilemma of environmental justice, an important institutional exploration is to set up environmental courts to carry out judicial specialization reform (Edwards, 2013). The environmental court unifies and centralizes the decentralized jurisdiction of environmental resource cases in the traditional court system, and improves the trial efficiency of environmental pollution liability disputes by enhancing the professional level of environmental justice, forming a strong constraint on resource waste and environmental pollution (Edwards, 2013; Carnwath, 2014). In November 2007, the country's first environmental court was established in Qingzhen, Guizhou Province, which was identified by the Supreme People's Court as one of the first "environmental judicial practice bases" in China[2]. The environmental court established an environmental expert advisory committee to reduce false trials and improve the efficiency of judicial handling of environmental cases. In July 2014, the Supreme People's Court established the Environmental and Resources Division in conjunction with the release of the "Opinions on Comprehensively Strengthening Environmental Resources Trial Work to Provide Effective Judicial Guarantee for Promoting Ecological Civilization Construction." These measures guide the promotion of judicial specialization and further provide a guarantee for the impartiality of environmental justice.

Hereafter, under the guidance of the Supreme People's Court, most of the provinces started to establish environmental courts. By the end of 2019, more than 100 environmental courts have been established across 20 provinces and municipalities in the country[3]. According to the "Trial of China's Environmental Resources (2019)" issued by the Supreme People's Court, the number of environmental resource trials has rapid growth and the efficiency of environmental justice has improved significantly compared with previous years.

3.2 Theoretical analysis

The "Porter hypothesis" points out that appropriate and reasonable environmental regulation will induce enterprises to innovate (Porter, 1991; Porter and van der Linde, 1995). The positive effect brought by this green-oriented innovation will compensate for the negative effect of the environmental cost that enterprises need to pay, and ultimately ease the dilemma between production and environmental degradation. Intuitively, the environmental court promotes the efficiency of environmental justice and law enforcement, directly or indirectly increasing the cost of environmental violations for enterprises that force them to carry out green technology innovation and improve production methods. First of all, the environmental court has unified the decentralized jurisdiction of environmental disputes in the traditional court system. The formation of such judicial specialization can greatly promote the efficiency of the trial of environmental pollution disputes, and effectively restrain the waste of resources and environmental pollution. Secondly, after the establishment of the environmental court, it usually adopts the mode of "trial-execution combination." This mode can greatly improve the traditional court's "only judgment without decision" situation in environmental cases and enhance judicial enforcement. Further, environmental courts endowed with direct enforcement power can also effectively alleviate the dilemma that the local environmental protection department has no enforcement power over polluting enterprises or is even interfered with by the local government. For polluting enterprises that seriously violate environmental regulations, the environment courts can use legal means such as seizure, detention, and property freezing to ensure that the enterprise abides by environmental judgments. Therefore, when enterprises face more efficient law enforcement brought by environmental courts and the extra cost due to environmental litigation, the best way for them to respond is through green technology innovation.

In addition, after the establishment of the environmental court, the centralized jurisdiction and centralized management of environmental violation cases provide a great convenience for public environmental litigation. Specialized case management meets the potential judicial needs of pollution victims or non-profit organizations that have nowhere to go when environmental justice is unclear. The clarification of the environmental litigation department and the simplification of the environmental judicial process not only reduces the cost of environmental litigation but also improves the judicial channels

2 https://www.chinacourt.org/article/detail/2022/11/id/7029003.shtml

3 For specific statistics, please refer to the "Trial of China's Environmental Resources (2019)" issued by the Supreme People's Court (https://www.court.gov.cn/zixun-xiangqing-228341.html).

for the public to participate in environmental protection rights, which can make polluting enterprises face greater supervision pressure. Moreover, specialized environmental litigation can also increase the public's expectations for environmental judicial rights protection, and the public is more willing to participate in environmental litigation to safeguard their legitimate rights and interests. In this way, environmental judicial deterrence and public supervision will form a synergy to generate stronger external supervision of polluting firms. As a result, public awareness of environmental needs and supervision will be significantly improved after the establishment of environmental courts. Enterprises will be pressured by public environmental supervision to carry out green technology innovations and achieve environmentally friendly production.

Based on the above analysis, hypotheses are proposed as follows:

Hypotheses 1. The establishment of the environmental court will promote corporate green technology innovation.

4 Methodology and data

4.1 Sample selection and data source

To accurately identify the changes in the green technology innovation capabilities of enterprises before and after the establishment of the environmental court, we select Chinese listed A-shared firms from 2004 to 2019 as the main research sample. The sample data are processed as follows: First, only all listed manufacturing firms from 2004 to 2019 are retained as samples; Second, firms with abnormal financial conditions such as ST and *ST are deleted[4]; Third, firms with a duration of fewer than 5 years are excluded; Fourth, firms with serious lack of financial indicators are deleted.

The data in this paper mainly comes from three parts: The firm green technology innovation data comes from the "China Research Data Service Platform (CNRS)." Specifically, we obtained it by matching the patent classification number information with the "International Patent Green Classification List" issued by the World Intellectual Property Organization (WIPO) in 2010. The data at the firm level comes from the "Cathay Pacific Database (CSMAR)." The city-level data comes from the "China City Statistical Yearbook."

4.2 Variable definition

(1) The dependent variable is firm green technology innovation, which is measured by the number of green patents. Considering the uncertainty and instability in the patent granting process and its vulnerability to bureaucratic factors, patented technologies may begin to have an impact on firms' production during the application process (Tan et al., 2014; Zhou et al., 2021). Therefore, the number of patent applications is more suitable to reflect the green technology innovation level of firms. According to the level of patent technology content, green patents are divided into green invention patents and green utility model patents. In this paper, we choose the total number of green patent applications (*TGpatent*), the applications of green invention patents (*GIpatent*), and green utility model patents (*GUpatent*) as the core explained variables.

(2) The Independent variable is a dummy variable (*Ecourt*) which is used to estimate the policy effect of the environmental courts in DID method. This paper regards the establishment of environmental courts as a quasi-natural experiment in justice reform. If a firm is located in the city that has established an environmental court and the data are from after the policy reform year, *Ecourt* is assigned a value of 1, otherwise, the value is 0. This paper uses the establishment of the prefecture-level city intermediate people's court as the core indicator. On the one hand, since we study green technology innovation at the firm level, the prefecture-level city intermediate people's court has closer contact with local firms in environmental cases than the high people's court, and the supervision effect is more direct. On the other hand, although there are a large number of environmental courts established by grassroots courts, it is difficult to verify the specific time of their establishment. At the same time, due to the fact that the judicial power of environmental protection tribunals in grassroots courts is mostly limited to districts and counties, and there are problems such as legal crises and lack of professionalism, they cannot fully affect the environmental cases of firms in the county or the whole city (Wang and Hang, 2014)

There are two levels of control variables. At the firm level, we control for firm characteristics including firm size (*Size*), firm age (*Age*), capital structure (*Leverage*), profitability (*Roa*), TobinQ (*TobinQ*), and cash holding level (*Cash*), and ownership concentration (*Share*). Considering that the results may be affected by the heterogeneity of cities, we also add the control variables to treat city characteristics including economic development level (*Rgdp*), the level of financial development (*Finance*), solid waste utilization (*Usage*) wastewater discharge (*Sewage*), Sulfur dioxide emissions (*So2*), and industrial soot emissions (*Dust*). The variable definitions and descriptive statistics are shown in Table 1.

4.3 Model specification

In this paper, we employ a DID model to examine the effect of the establishment of environmental courts on firms' green technology innovation. A common setting for the DID model is to add an interaction of policy dummy variables (used to distinguish affected groups) and time dummy (used to identify the time before and after the shock). The interaction term captures the real effect of policy shocks. In this way, we set the DID model as follows:

4 ST refers to the listed firms operating losses for two consecutive years. These firms' financial or other conditions are abnormal and the stock trading has been specially treated; *ST refers to the listed firms operating losses for three consecutive years, and their stocks have been warned of the risk of delisting.

TABLE 1 Variable definition and descriptive statistics.

Variables	Definition	Observations	Mean	Std. Dev.	Min	Max
TGpatent	The natural logarithm of one plus the total number of green patent applications	5,413	1.719091	0.9529987	0	7.062449
GIpatent	The natural logarithm of one plus the number of green invention patent applications	5,413	1.252614	0.9752521	0	6.912743
GUpatent	The natural logarithm of one plus the number of green utility model patent applications	5,413	1.008903	0.8908621	0	6.460217
Ecourt	= 1 if a firm is located in a city that established an environmental court; = 0 otherwise	5,413	0.2033992	0.4025642	0	1
TobinQ	The ratio of firm market value to capital replacement cost	5,413	1.867043	0.9677244	0.876518	6.133729
Cash	The ratio of net cash flow from operating activities to total assets	5,413	0.136287	0.1234328	0.003305	0.584157
Top1	The shareholding ratio of the largest shareholder (%)	5,413	35.90809	15.44961	8.33	76.53
Roa	The ratio of net profit to total assets	5,413	0.0425689	0.052972	−0.156914	0.20897
Debt	The ratio of total liabilities to total assets	5,413	0.3855161	0.1945142	0.0388973	0.8492782
Age	The natural logarithm of the firm age	5,413	15.75371	5.289997	5.75	30.33333
Size	The natural logarithm of the total assets	5,413	22.15076	1.308109	19.95498	25.9992
Rgdp	The natural logarithm of real GDP	5,413	17.52677	1.018729	10.77164	19.32653
Sewage	The natural logarithm of city wastewater discharge	5,413	9.322322	0.875856	5.537334	11.47731
So2	The natural logarithm of city sulfur dioxide emissions	5,413	10.30801	1.36099	6.72022	13.43414
Dust	The natural logarithm of city soot emissions	5,413	9.819983	1.216778	5.659482	15.45815
Usage	The comprehensive utilization rate of solid waste	5,413	4.424293	0.2429924	1.94591	4.964242
Finance	The proportion of financial institution loan balance to GDP at the end of the year	5,413	2.609472	2.793001	0.1467231	180.3978

$$Greeninv_{ict} = \beta_0 + \beta_1 \times Ecourt_{ct} + \beta_2 \times X_{ict} + \beta_3 \times Z_{ct} + \mu_i + \lambda_t + \varepsilon_{ict} \quad (1)$$

Where the subscript i is the firm, c is the city location and t is the year. The dependent variable is the firm green technology innovation ($Greeninv_{ict}$). We use the natural logarithm of one plus the applications for the total number of green patents ($TNpatent$), green invention patents ($GIpatent$), and green utility model patents ($GUpatent$) to measure the firms' green technology innovation. The core independent variable is the dummy ($Ecourt_{ct}$) which indicates whether city c has set up the environmental courts in year t, and its coefficient β_1 represents the effect of the establishment of environmental courts on firms' green technology innovation. X_{it} represents a set of control variables affecting the firms' green technology innovation, Z_{ct} represents a set of control variables at the city level. All the control variables adopt the value lagged one period. μ_i and λ_t are the firm and time fixed effects, respectively. ε_{ict} represents the random disturbance. All the standard errors in our regressions are clustered at the city level to control for the possible intergroup correlations.

5 Empirical results and analysis

5.1 Basic results

The baseline regression results are based on model (1). After controlling city and year fixed effects, the basic estimation results of this paper are presented in Table 2. Columns (1) and (2) take the total number of green patent applications ($TGpatent$) as the independent variable. The coefficients of the policy variable ($Encourt$) are all significantly positive at 1% confidence level whether we add control variables or not, indicating that the establishment of the environmental courts had a positive impact on the green invention patent. As for columns (3) and (4), we take green invention patents ($GIpatent$) as the dependent variable. The coefficients of *Ecourt* are significantly positive whether adding control variables or not, indicating that the establishment of environmental courts can also promote the firm green invention patent applications. Columns (5) and (6) report the regression results for green utility patent applications ($GUpatent$). We find similar results, but the coefficients of *Ecourt* for $GUpatent$ are smaller which indicates that environmental courts play a greater role in promoting high-tech green innovation than low-tech green innovation. In sum, our basic results support the *Porter*

TABLE 2 Baseline results.

	Total green technology innovation		High-tech green innovation		Low-tech green innovation	
	TGpatent	*TGpatent*	*GIpatent*	*GIpatent*	*GUpatent*	*GUpatent*
	(1)	(2)	(3)	(4)	(5)	(6)
Ecourt	0.2266***	0.2104***	0.2239***	0.2029***	0.1834***	0.1739***
	(0.054)	(0.051)	(0.063)	(0.057)	(0.039)	(0.049)
TobinQ		0.0025		0.0042		0.0046
		(0.015)		(0.017)		(0.018)
Cash		0.2247		0.3324*		0.1235
		(0.173)		(0.191)		(0.138)
Top1		0.0048		0.0058*		0.0040
		(0.003)		(0.003)		(0.003)
Roa		0.3550		0.1699		0.4621*
		(0.231)		(0.240)		(0.253)
Debt		0.0659		0.0730		−0.0210
		(0.213)		(0.247)		(0.176)
Age		0.1754***		0.1550***		0.1668**
		(0.043)		(0.017)		(0.075)
Size		0.2360***		0.2573***		0.1453***
		(0.049)		(0.049)		(0.044)
Rgdp		0.6346		0.7199		0.3680
		(0.562)		(0.629)		(0.456)
Sewage		0.0906		0.0884		0.1103*
		(0.059)		(0.064)		(0.057)
So2		0.0291		−0.0013		0.0457
		(0.033)		(0.036)		(0.028)
Dust		−0.0070		0.0027		−0.0007
		(0.023)		(0.024)		(0.027)
Usage		0.1887**		0.1682**		0.1289
		(0.080)		(0.075)		(0.089)
Finance		0.0462		0.0561		0.0493
		(0.065)		(0.070)		(0.053)
Constants	0.7782***	−17.7907*	0.2690*	−19.7775*	0.4965***	−11.8421
	(0.159)	(9.280)	(0.147)	(10.312)	(0.180)	(7.724)
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
R-squared	0.187	0.217	0.198	0.222	0.128	0.145
Observations	6,036	5,413	6,036	5,413	6,036	5,413

Notes: The standard errors are represented in parentheses. All regressions adopt standard errors clustered at the city level. *, **, and *** indicate 10, 5, and 1% significance levels, respectively.

TABLE 3 Parallel trend Test.

	TGpatent	*GIpatent*	*GUpatent*
	(1)	(2)	(3)
Ecourt_5	0.0414	0.0150	0.0106
	(0.105)	(0.119)	(0.073)
Ecourt_4	−0.0102	−0.0591	0.0435
	(0.081)	(0.095)	(0.067)
Ecourt_3	0.0621	0.0248	0.0794
	(0.073)	(0.086)	(0.052)
Ecourt_2	0.0035	−0.0407	0.0254
	(0.051)	(0.060)	(0.058)
Current	0.1763***	0.1678***	0.1056
	(0.065)	(0.061)	(0.066)
Ecourt1	0.1938***	0.1601**	0.2041***
	(0.064)	(0.080)	(0.053)
Ecourt2	0.3069***	0.2419***	0.2913***
	(0.076)	(0.089)	(0.069)
Ecourt3	0.3562***	0.3074***	0.2690***
	(0.063)	(0.073)	(0.066)
Ecourt4	0.4142***	0.3433***	0.3777***
	(0.110)	(0.105)	(0.110)
Ecourt5	0.2658*	0.2377*	0.3098**
	(0.137)	(0.135)	(0.135)
Constant	−17.6350*	−19.6857*	−10.7733
	(9.561)	(10.707)	(7.823)
Control variables	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
R-squared	0.220	0.223	0.147
Observations	5,413	5,413	5,413

Notes: The standard errors are represented in parentheses. All regressions adopt standard errors clustered at the city level. *, **, and *** indicate 10, 5, and 1% significance levels, respectively.

Hypothesis and provided evidence that environmental courts can encourage firms to commit to green transformation and innovation. Moreover, the role of environmental courts in firm green technology innovation is reflected in the promotion of high-tech innovation.

5.2 Parallel trend test and dynamic effects

To ensure the validity of DID estimation, the parallel trend assumption must be satisfied which requires that there is no significant difference in the green technology innovation between the treatment group and control group firms before the establishment of environmental courts when controlling for other factors.

With regard to this assumption, referring to Jacobson et al. (1993), we divide the variable *Ecourt* into a set of interaction terms between environmental courts status and dummy variables relative to the setting year of environmental courts. The specific estimation equation is as follows:

$$Greeninv_{ict} = \beta_0 + \sum_{n=-5, n \neq 0}^{5} \theta_n \times Ecourt_{c,t+n} + \beta_2 \times X_{ict} + \beta_3 \times Z_{ct} + \mu_i + \lambda_t + \varepsilon_{ict} \quad (2)$$

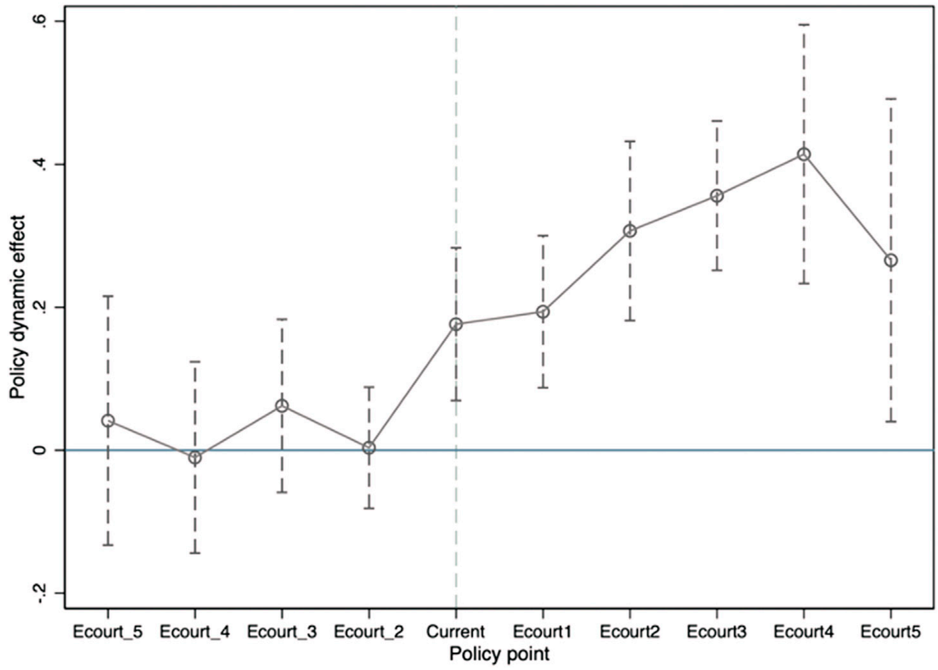

FIGURE 1
Parallel trend Test for *TGpatent*.

Where $Ecourt_{c,t+n}$ represents the *n*th year relative to the setting year of environmental courts. $n < 0$ indicates the *n*th year before the setting year. $n > 0$ indicates the *n*th year after the setting year of environmental courts, and $n = 0$ represents the setting year of the environmental courts. Since our sample period is from 2004 to 2019, we set $n = -5$ if $n < -5$ and $n = 5$ if $n > 5$ as the two endpoints to make the best use of data information and reduce estimation errors. Furthermore, to avoid collinearity in the regression, we take $n = 0$ as the base year.

Table 3 presents the regression results of the parallel trend test. Figure 1 shows the parallel trend charts *TGpatent*, and the charts for *GIpatent* and *GUpatent* are shown in Supplementary Figures A1, A2 in Supplementary Appendix A1. We observe that before the environmental courts' establishment ($n \leq 1$), the value of coefficients θ_n are near to 0 and insignificant, suggesting that before the establishment of environmental courts, there was no significant difference in the firms' green technology innovation between the treatment group and the control group. After setting up the environmental courts ($n > 0$), it can be found that both the magnitude and significance of θ_n have significantly increased. The above results demonstrate that the parallel trend assumption has been satisfied and our empirical analysis is valid.

Moreover, we also find that the duration of the positive dynamic effect of environmental courts lasts for approximately 4 years, indicating that the positive effect of environmental justice reform is sustainable.

5.3 Robustness checks

5.3.1 PSM-DID

Ideally, in our regression, the treatment and control group firms are identical in all aspects except whether one firm is located in the city with an environmental court or not. In reality, this case hardly exists and there is often a problem of sample self-selection bias. So, to alleviate the possible self-selection bias, we combine the propensity score matching (PSM) and DID method to re-examine the baseline regressions. Specifically, we first select individual firm characteristics including firm size (*Size)*, firm age (*Age*), capital structure (*Leverage*), profitability (*Roa*), TobinQ (*TobinQ*), cash holding level (*Cash*), and ownership concentration (*Share*) as matching variables. Then we use the 1: 1 nearest neighbor matching to conduct PSM. Finally, we run the DID regressions on the new PSM samples.

Table 4 shows the regression results of the PSM-DID estimation. And the results of the sample data balancing test after the matching is shown in Supplementary Table A1 in the Supplementary Appendix A1. The estimation results are similar to the baseline results. The coefficient of the policy variable (*Ecourt*) is significantly positive, indicating that the establishment of environmental courts can promote firms' green technology innovation in the pilot area. Overall, although the coefficients of our interest under PSM-DID are larger than that in the baseline results, it is still positively significant which proves that our baseline results above are robust.

5.3.2 Tobit and negative binomial regression

Although the overall distribution of the patent data is spread over a wide range of positive values, it is also relatively concentrated at zero values. Given this distribution of the dependent variable, it may be difficult to obtain a consistent estimate through ordinary least squares (OLS) (Davidson and MacKinnon, 2004). In such cases, the Tobit model is a more suitable method to solve the problem of such a censored dependent variable. In addition, we also performed regressions with a zero-inflated negative binomial

TABLE 4 PSM-DID estimation.

	Total green technology innovation		High-tech green technology innovation		Low-tech green technology innovation	
	TGpatent	TGpatent	GIpatent	GIpatent	GUpatent	GUpatent
	(1)	(2)	(3)	(4)	(5)	(6)
Ecourt	0.2259***	0.2245***	0.2253***	0.2164***	0.1942***	0.1909***
	(0.055)	(0.052)	(0.064)	(0.057)	(0.042)	(0.051)
Constants	0.7182***	−18.9117**	0.1884	−24.0837**	0.4331**	−11.0716*
	(0.180)	(9.137)	(0.149)	(9.824)	(0.210)	(6.610)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
R-squared	0.188	0.213	0.199	0.220	0.126	0.138
Observations	5,189	4,708	5,189	4,708	5,189	4,708

Notes: The standard errors are represented in parentheses. All regressions adopt standard errors clustered at the city level. *, **, and *** indicate 10, 5, and 1% significance levels, respectively.

TABLE 5 Results with Tobit and ZINB models.

	Tobit regression			ZINB regression		
	TGpatent	*GIpatent*	*GUpatent*	*TGpatent*	*GIpatent*	*GUpatent*
	(1)	(2)	(3)	(4)	(5)	(6)
Ecourt	6.3233***	10.8637***	6.5294***	0.2622***	0.3125***	0.2651***
	(1.880)	(1.557)	(0.756)	(0.040)	(0.047)	(0.052)
Constant	−284.236***	−251.171***	−76.921***	0.3108	−0.7539	1.0883
	(22.800)	(19.023)	(9.320)	(0.805)	(0.959)	(1.033)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
Observations	5,413	5,413	5,413	4,920	4,856	4,620

Note: The standard errors are represented in parentheses. ***, **, and * represent different significance levels, indicating $p < 0.01$, $p < 0.05$, and $p < 0.1$, respectively.

regression model (ZINB) for the robust test. Table 5 reports the regression results. The coefficients of the core independent variable (*Ecourt*) are positively significant and consistent with the baseline regression results. The above regression results once again prove the robustness of the baseline results, indicating that the establishment of environmental courts significantly promotes the green technology innovation of Chinese firms.

5.3.3 Placebo test

To further that our results are not biased due to random chance, we perform a bootstrapping placebo test following Cai et al. (2016) and Ma et al. (2021) by randomly assigning environmental court setting status to cities. Specifically, we randomly assign the environmental courts setting status to different years during our research period while assuming that the total number of environmental courts in our research is fixed, and then. For instance, 8 cities set up the environmental courts in 2014, so we randomly select 1 year from our sample period as the setting year and construct a *false* treatment dummy, i.e., $Ecourt_{ct}^{false}$. Then, we run the baseline DID regressions based on the pseudo-sample and repeat this randomization process 500 times. If real policies do play a role, then the newly constructed variables of interest should have no impact on green technology innovation. The distribution of the false coefficients and their associated *p*-values for *TGpatent* are shown in Figure 2. Supplementary Figures A3, A4 show the results for *GIpatent* and *GUpatent* in Supplementary Appendix A1. The distributions center around zero and most of the *p*-values are larger than 0.1. At the same time, our true estimators (red lines denote the true value of coefficients in Table 2) are clear outliers. These results indicate that our baseline results are not severely biased due to any random chance which verifies the robustness of our analysis.

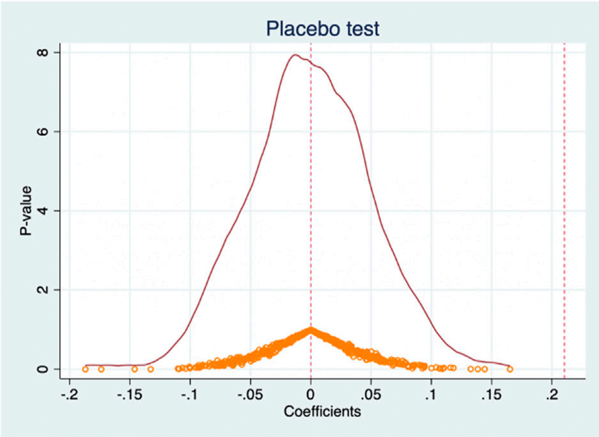

FIGURE 2
Placebo test for *TGpatent*.

6 Influencing mechanism analysis

According to the theoretical hypothesis above, On the one hand, the establishment of environmental courts can improve the judicial fairness and efficiency of environmental cases and increase the risk of environmental litigation faced by enterprises, thus enabling enterprises to carry out green technology innovation. On the other hand, the establishment of environmental courts has also promoted the environmental awareness of the public (Edwards, 2013). With the improvement of the public's awareness of environmental protection, enterprises will also be subject to the corresponding pressure of environmental supervision from the public, so as to carry out green technology innovation. As a result, we empirically test the potential mechanisms behind the green technology innovation effect brought by the environmental court from two aspects of judicial pressure and external supervision pressure.

Referring to the method proposed by Baron and Kenny (1986), we construct mediating effect models to test the underlying influence mechanism above. Specific steps are as follows. First, the intermediary variables of environmental penalty cases are used as the dependent variables, and the establishment of environmental courts is used as an independent variable to run the regression model (3). Then, we take corporate green technology innovation as the dependent variable and the intermediary variable as the independent variable to run the regression model (4). Finally, we include green technology innovation, the intermediary variables, and policy variables in the regression model (5) to estimate the policy effect of environmental courts. The mediating effect exists only if coefficients α_1; δ_1 and θ_2 are significant and θ_1 becomes smaller than β_1 in the model (1) or less significant. And then, the theoretical mechanism described above can be established through the mediating effect test.

$$Mid_{ct} = \alpha_0 + \alpha_1 \times Ecourt_{ct} + \varphi \times X_{ict} + \gamma \times Z_{ct} + \mu_i + \lambda_t + \varepsilon_{ict} \quad (3)$$

$$Greeninv_{ict} = \delta_0 + \delta_1 \times Mid_{ct} + \varphi \times X_{ict} + \gamma \times Z_{ct} + \mu_i + \lambda_t + \varepsilon_{ict} \quad (4)$$

$$Greeninv_{ict} = \theta_0 + \theta_1 \times Ecourt_{ct} + \theta_2 \times Mid_{ct} + \varphi \times X_{ict} + \gamma \times Z_{ct} + \mu_i + \lambda_t + \varepsilon_{ict} \quad (5)$$

In models (3)–(5), *Mid* are the intermediary variables that represent the environmental litigation pressure and the external supervision pressure. We take the number of regional environmental penalty cases (*Punishcase*) to proxy the environmental litigation pressure (Zhang et al., 2019). The data of regional environmental penalty cases are manually collected by the authors from specialized environmental litigation websites[5]. For external supervision pressure, we measured it in two ways. First, we use the logarithm of the number of environmental complaint letters received by regional government departments (*Emletter*). The related data are collected from the "China's Environmental Yearbook." Then, we take Baidu Index on environmental pollution to proxy for the level of external supervision pressure (*Baidu*). In China, Baidu's search engine has a market share of more than 80%. Baidu Index reflects the attention of Internet users to a certain field when using Baidu's search engine. This pressure of public attention has a huge impact on corporate decision-making. Referring to Kahn and Kotchen (2011) and Zheng et al. (2012), we use Python to crawl the Baidu index of each city with the keyword "environmental pollution."

The regression results of the mediating effect tests are shown in Table 6. Columns (1)–(2) show the mechanism test of environmental litigation pressure. The regression coefficient of *Ecourt* in column (1) is 0.1468 and statistically significant, suggesting that environmental courts raise litigation pressure on firms. In column (2), both the *Ecourt* and *Punishcase* variables are included in the regression model. The coefficient of *Ecourt* is 0.2516, which is significant and smaller than that in the baseline model when the intermediate variable is not included, proving the existence of the mediating effect of environmental litigation pressure and indicating that environmental courts increase corporate green technology innovation by imposing environmental litigation pressure on firms.

Another potential channel through which environmental courts can influence green technology innovation is external supervision pressure. Columns (3)–(6) in Table 6 show the results of this mediating effect. Similarly, the coefficients of *Ecourt* in columns (3) and (5) are significantly positive, which shows that environmental courts promote public awareness of environmental protection. Columns (4) and (6) incorporate both the *Ecourt* and intermediate variables into the regression model. The regression coefficients of *Ecourt* are positively significant and relatively smaller than the result in the baseline model which proves the mediating effect of external supervision pressure and indicates that environmental courts promote green technology innovation by imposing external supervision pressure on firms.

Combining the above empirical results, it can be concluded that the environmental courts have improved the efficiency of environmental

5 The data on environmental penalty cases is obtained from the China Judgments Online website, where verdict documents are publicly available (http://wenshu.court.gov.cn).

TABLE 6 The results of the mechanism analysis.

	Environmental litigation pressure		External supervision pressure			
	Punishcase	*TGpatent*	*Emletter*	*TGpatent*	*Baidu*	*TGpatent*
	(1)	(2)	(3)	(4)	(5)	(6)
Ecourt	0.1468**	0.1561***	0.1368*	0.0605***	0.0420**	0.1258***
	(0.060)	(0.046)	(0.078)	(0.026)	(0.017)	(0.029)
Punishcase		0.0449***				
		(0.011)				
Emletter				0.0189**		
				(0.010)		
Baidu						0.0120***
						(0.004)
Constant	−15.8705	−12.7339	7.1466***	−4.2494***	8.9786	−20.6920
	(34.051)	(14.722)	(1.369)	(1.629)	(6.060)	(13.163)
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
R-squared	0.11	0.082	0.025	0.059	0.27	0.131
Observations	3,931	3,931	2066	2066	4,287	4,287

Notes: The standard errors are represented in parentheses. All regressions adopt standard errors clustered at the city level. *, **, and *** indicate 10, 5, and 1% significance levels, respectively.

TABLE 7 The level of local law environment.

	Low level of law environment			High level of law environment		
	TGpatent	*GIpatent*	*GUpatent*	*TGpatent*	*GIpatent*	*GUpatent*
	(1)	(2)	(3)	(4)	(5)	(6)
Ecourt	0.1779*	0.2166*	0.0786	0.2338***	0.1936***	0.2348***
	(0.106)	(0.114)	(0.100)	(0.062)	(0.069)	(0.064)
Constant	−13.8132	−7.5947	−10.9177	−17.8420	−28.3599**	−4.5994
	(9.771)	(11.318)	(8.397)	(11.967)	(12.479)	(7.984)
Control Variables	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
R-squared	0.220	0.215	0.186	0.230	0.241	0.141
Observations	1879	1879	1879	3,534	3,534	3,534

Notes: The standard errors are represented in parentheses. All regressions adopt standard errors clustered at the city level. *, **, and *** indicate 10, 5, and 1% significance levels, respectively.

justice and the enforcement of punishment so that firms will face higher litigation risks and illegal costs. In addition, the environmental courts meet the public's environmental rights protection needs, thereby enhancing public awareness of environmental protection. Therefore, firms will invest more in green technology innovation activities when facing the pressure of environmental litigation and external supervision brought by the environmental court.

7 Further analysis

7.1 Local law environment

The improvement of the judicial system provides a guarantee for the validity and enforcement of the law, and a sound legal system environment is the basis for the effectiveness of the judicial system.

TABLE 8 Local government intervention.

	Low level of intervention			High level of intervention		
	TGpatent	*GIpatent*	*GUpatent*	*TGpatent*	*GIpatent*	*GUpatent*
	(1)	(2)	(3)	(4)	(5)	(6)
Ecourt	0.1304	0.1275	0.0918	0.2428***	0.2233***	0.2114***
	(0.092)	(0.094)	(0.098)	(0.059)	(0.073)	(0.052)
Constant	−9.2361	−9.9778	−14.7269	−26.0206**	−28.5109**	−12.3949
	(12.810)	(11.879)	(10.530)	(11.632)	(14.229)	(10.134)
Control Variables	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
R-squared	0.262	0.268	0.169	0.215	0.219	0.146
Observations	1,454	1,454	1,454	3,959	3,959	3,959

Notes: The standard errors are represented in parentheses. All regressions adopt standard errors clustered at the city level. *, **, and *** indicate 10, 5, and 1% significance levels, respectively.

Therefore, to examine the effectiveness of the environmental justice system, we must consider the differences between local environmental legislation and legal systems. We selected the number of local environmental laws and regulations promulgated by each region as the proxy for the local law environment, the relevant data can be obtained in the "China Environmental Statistics Yearbook". Simultaneously, based on the median number of local environmental laws and regulations, we divided the sample into low and high law environment. The specific regression results are shown in Table 7. Columns (1)–(3) report the coefficients of *Ecourt* on green technology innovation in the subsample of low level of law environment and the coefficients are positive and significant at 10% level while the coefficient of *GUpatent* is insignificant. Columns (4)–(6) show a significant positive impact of environmental courts on firm green technology innovation in the subsample of the high level of law environment. The results indicate that when the firm is located in a region with a better law environment, the environmental court can better play its role and combine with local laws and regulations to promote the green technology innovation ability of the firm.

7.2 Local government intervention

In China, the constraint of environmental regulation on environmental pollution may be weakened by the existence of local government intervention. According to Li and Zhou (2005), local government officials often pursue the desired economic outcomes under the pressure of political promotion. Then in this case, local governments may ignore the pollution behavior of enterprises for the sake of local economic performance, or even interfere with judicial justice in order to safeguard relevant interests.

Therefore, if the establishment of environmental courts can bring external cost pressure to enterprises and encourage relevant pollution firms to carry out green technology innovation, a question worth exploring is how government intervention affects our precious results? To answer this, we divided the samples into two groups, high and low levels of government intervention according to the marketization index, and performed regressions respectively. The regression results are shown in Table 8. We find that the coefficients of *Ecourt* in columns (4)–(6) are significantly positive at the 1% confidence level, while the coefficients of *Ecourt* in columns (1)–(3) are insignificant, indicating that the role of environmental courts in promoting firms' green technology innovation is more pronounced in areas with severer government intervention. This result also means that the strengthening of the legal system brought about by the environmental court helps to weaken the government's protection of local firms and maintain legal authority.

7.3 Differences in firms' ownership

In China, the differences between SOEs and non-SOEs can not be ignored in terms of financial support and government connections (Piotroski and Wong, 2012). Specifically, Due to the nature of their relationship with local governments, SOEs are more vulnerable to government favoritism, especially when facing certain policy shocks compared with non-SOEs. Therefore, there are differences in performance and behavioral manifestations among enterprises with different ownership (Gadenne et al., 2009). In this subsection, we further examine the effect of environmental courts on a firm's green technology innovation considering ownership structures. Table 9 presents the group regression results based on ownership. Columns (1)–(3) takes SOEs as the research samples. The coefficients of *Ecourt* are insignificant. While in columns (4)–(6) which take non-SOEs as the samples, the coefficients of *Ecourt* are positively significant at 1% confidence level. The results show that the promoting effect of environmental court on firms' green technology innovation is more pronounced in SOEs rather than non-SOEs.

TABLE 9 Differences in firms' Ownership.

	State-owned			Non-state-owned		
	TGpatent	*GIpatent*	*GUpatent*	*TGpatent*	*GIpatent*	*GUpatent*
	(1)	(2)	(3)	(4)	(5)	(6)
Ecourt	0.2869***	0.2738***	0.2249***	0.1250	0.1024	0.1115
	(0.057)	(0.062)	(0.059)	(0.088)	(0.093)	(0.091)
Constant	−17.4550	−23.5103*	−14.1225	−22.8169**	−21.5804*	−15.3314
	(13.511)	(13.274)	(11.975)	(10.617)	(11.791)	(9.853)
Control Variables	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
R-squared	0.155	0.157	0.138	0.281	0.276	0.179
Observations	2,993	2,993	2,993	2,266	2,266	2,266

Notes: The standard errors are represented in parentheses. All regressions adopt standard errors clustered at the city level. *, **, and *** indicate 10, 5, and 1% significance levels, respectively.

8 Conclusion

As an important reform of environmental protection undertaking in China, the establishment of the environmental courts not only improve the environmental judicial system but also provides an important institutional guarantee for the coordinated development of the environment and economy. There's great practical significance to explore the economic effect of environmental court on firm green transformation. Taking Chinese A-share listed firms from 2003 to 2019 as our research samples, we adopt the DID method to investigate how the establishment of environmental courts affects corporate green transformation from the perspective of green technology innovation. Our study provides empirical evidence proving that the establishment of environmental courts significantly promotes green technology innovation among enterprises which also supports the Porter hypothesis, and compared with low-tech green innovation, environmental courts play a greater role in promoting high-tech green innovation. In addition, the potential mechanisms behind the results are that the more effective judicial enforcement and better public awareness of environmental supervision brought by the environmental court have increased the cost of illegality and external supervision pressure for firms, which will enable firms to carry out green technology innovation. Furthermore, the impact of environmental courts on corporate green technology innovation also depends on the nature of the enterprises and the regions in which the enterprises are located. That is, the positive impact of the environmental court is more pronounced in SOEs and firms located in regions where local protectionism is more serious. At the same time, in regions with a more perfect environmental legal system, environmental courts have more significant promoting effects on green technology innovation.

Our findings have clarified the impact of environmental courts on corporate green technology innovation and its potential influencing mechanism and provided enlightenment and guidance to policymakers to further promote the green transformation of enterprises. First, the results show that environmental courts can promote green technology innovations and the effect is closely related to judicial efficiency and the law environment. Policymakers should further improve various systems in environmental courts and combine judicial enforcement to formulate effective environmental regulations and policies. Second, considering that public participation is an indispensable part of environmental governance, policymakers should let the public know about environmental courts through publicity, announcements, *etc.*, so as to give full play to the role of environmental courts to increase public participation in environmental protection.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: https://www.gtarsc.com.

Author contributions

Conceptualization, ST; methodology, MH and ZF; software, ST and DZ; validation, ST; formal analysis, ST and MH; resources, ZF and DZ; data curation, ST and ZF; writing-original draft preparation, ST; writing-review and revision on original draft, ST and MH; supervision, ZF and DZ. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2023.1090853/full#supplementary-material

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frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 07 April 2023
DOI 10.3389/fenvs.2023.1062147

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OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Environmental Economics and Management, a section of the journal Frontiers in Environmental Science

RECEIVED 05 October 2022
ACCEPTED 28 March 2023
PUBLISHED 07 April 2023

CITATION
Wu T, Jia W and Wang Q (2023), Deviation between willingness and actual behavior regarding community participation in protected areas: A case study in Shengjin lake national nature reserve in China. *Front. Environ. Sci.* 11:1062147. doi: 10.3389/fenvs.2023.1062147

Deviation between willingness and actual behavior regarding community participation in protected areas: A case study in Shengjin lake national nature reserve in China

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Introduction: The deviation between high willingness and poor actual behaviors in community participation has become an obstacle to achieving effective management and resource protection of protected areas. Therefore, it is necessary to investigate this deviation and its influencing factors.

Methods: Based on a field survey of community residents in the Shengjin Lake National Nature Reserve (SJLNNR) in Anhui Province, China, this study uses a Logistic-ISM model to analyze the key factors influencing the deviation and the hierarchical structure supporting those key factors.

Results: There is a significant deviation between participation willingness and actual behavior in SJLNNR. This deviation is characterized by eight key factors. Among these, awareness of the necessity of establishing SJLNNR is a direct factor at the surface level. Participation of important or recognizable people; average annual family income; understanding of environmental protection laws and regulations; realization of environmental improvement effect; satisfaction with SJLNNR authority; and future earnings expectations are all intermediate indirect factors. Furthermore, resident member is a fundamental factor. Resident members refer to those who live at home for six months or more during a calendar year.

Discussion: These results indicate that there are three possible practical reasons for the deviation: 1) The lack of young and middle-aged adults is the root cause. 2) Inadequate ecological compensation is the direct trigger. 3) Individual internal psychological factors have significant effects. Furthermore, this study provides policy implications for converting willingness into actual participation in the community and promoting sustainable development.

KEYWORDS

protected areas, sustainable development, community participation, willingness and behavior, deviation, China

1 Introduction

Protected areas (PAs) play a critical role in protecting landscapes, safeguarding wildlife habitats, and conserving biodiversity (Watson et al., 2014; Schirpke et al., 2017; Liu et al., 2022; Wu et al., 2022). Over the past few decades, the establishment of PAs has become a worldwide conservation strategy (Liévano-Latorre et al., 2021), and PAs have undergone significant expansion, both in area and quantity (Watson et al., 2014; Wang and Liu, 2022). However, wide variation still exists in the quality of conservation management, which hinders PAs from achieving their conservation goals (Chidakel and Child, 2022). Many researchers have noted that the effective management of PAs is crucial for successful conservation outcomes and sustainable development (Coad et al., 2013; Rezende Oliveira et al., 2019; Riggio et al., 2019; Lwin et al., 2022).

Community participation stems from the concept of community development, which refers to the process of promoting the development of communities through the spontaneous involvement of residents in various community activities and affairs (Zhang et al., 2020b). Community participation in the management of PAs is of great importance for effective management (Islam et al., 2017; Zhang et al., 2020b; Sagoe et al., 2021; Freitas et al., 2022), and is regarded as a precondition for success (Huber and Arnberger, 2021). In addition, it reduces conflict between the local community and the management agency by considering the basic needs of residents (Zhang J et al., 2020), and working to alleviate poverty (Jiang and Wu, 2021), achieving a win-win scenario in nature protection and socioeconomic development (Peng et al., 2021; Masud et al., 2022).Nowadays, it is widely recognized that local community members should be entitled to and encouraged to participate in PA management. Specifically, community members should first abide by PA regulations and rules. In terms of the formulation and implementation of policies and plans for PAs, they have decision-making powers through consultation, meetings, negotiations, and public hearings (Niedziałkowski et al., 2018). In daily life, they can supervise and report human activity that has harmful influences on the environment (Lai, 2022). Furthermore, they are encouraged to actively engage in the eco-tourism business, ecological projects, and development projects of PAs, carried out by government or Non-Governmental Organizations (NGO) to share benefits (e.g., economic earnings, skill training, PA employment, and other job opportunities) while promoting PA construction (Sirivongs and Tsuchiya, 2012; Ma et al., 2017).

However, several studies have found that meaningful community participation in the management of PAs is far from adequate (Trimble et al., 2014; Bockstael et al., 2016; Zhang et al., 2020b; Gordon-Cumming and Mearns, 2020), although most local communities and residents are willing to participate in nature conservation (Trimble et al., 2014; Araia and Chirwa, 2019; Gordon-Cumming and Mearns, 2020; Hing and Riggs, 2021; Jiang and Wu, 2021). For example, small-scale fishers in PAs have shown great interest in participating in fisheries management; however, the number of fishers that attend the meetings related to policy decision-making with the government has been very low (Trimble et al., 2014). Furthermore, under the premise that 90% of the local people investigated showed a willingness to be involved in conservation, approximately 73% not only took no action but also violated indigenous forests rules (Araia and Chirwa, 2019). This puzzling phenomenon has also been observed in China. For instance, Lan (2020) discovered that community residents around Giant Panda National Park have accumulated deep feelings toward giant pandas and have high enthusiasm for the protection of giant pandas and national park management. However, residents rarely expressed opinions or suggestions in relevant public hearings held by the community. In Wanglang National Nature Reserve in Sichuan Province, farmers were highly supportive of participating in community grazing management, but they took no action (Lai, 2022).

Thus, previous research has revealed that there is a huge deviation between willingness and actual behavior in terms of community participation in PAs. Specifically, community residents who are highly willing to participate in the management and construction of PAs tend to take no action. Subsequently, two intuitive questions that resulted from this finding were as follows: 1) What caused the contradiction between the high willingness of community residents and their poor participation behavior? 2) How can participation willingness be transformed into actual behavior? The answers to these two questions are important for promoting effective community participation and realizing sustainable development.

Generally, willingness predicts and leads to the realization of the corresponding actual behavior of an individual; however, many previous studies have confirmed that there is a deviation between willingness and behavior in real life, such as in commodity consumption (Wang and Li, 2022), services purchases (Qu et al., 2022), e-commerce adoption (Li et al., 2020), and land transfer (Zhang et al., 2020a). This deviation has been further identified in the field of pro-environmental behaviors such as green consumption (Rausch and Kopplin, 2021; Wang et al., 2021; Ma et al., 2022; Qiu et al., 2022), green agriculture (Guo et al., 2021; Li et al., 2021), garbage classification (Kuang and Lin, 2021; Zhang et al., 2022; Zhou et al., 2022), bird conservation donation (Eylering et al., 2022), and renewable energy development support (Fang et al., 2021). All these studies concluded that the willingness of an individual is higher than the actual behavior demonstrates. In other words, some people with pro-environmental willingness do not take practical actions, which means that there may be obstacles in the conversion from willingness to behavior. Therefore, researchers have investigated the factors influencing the pro-environmental willingness-behavior connection. For instance, Li et al. (2021) exploited the theory of planned behavior (TPB) (Ajzen et al., 1991), and reveal that the deviation between the willingness of farmers to adopt photovoltaic agriculture and actual adoption centers around seven factor: farming experience, production specialization, distance to nearest photovoltaic enterprises, usefulness perception, ease of use perception, technical training, and photovoltaic investment cost. Rausch and Kopplin (2021) focused on the purchasing behavior of consumers toward sustainable clothing. The study determined that perceived aesthetic risk has a negative impact on the willingness-behavior relationship.

In terms of willingness and behavior to participate in PA management, there are few relevant studies. On the one hand, some researchers have investigated the factors influencing the

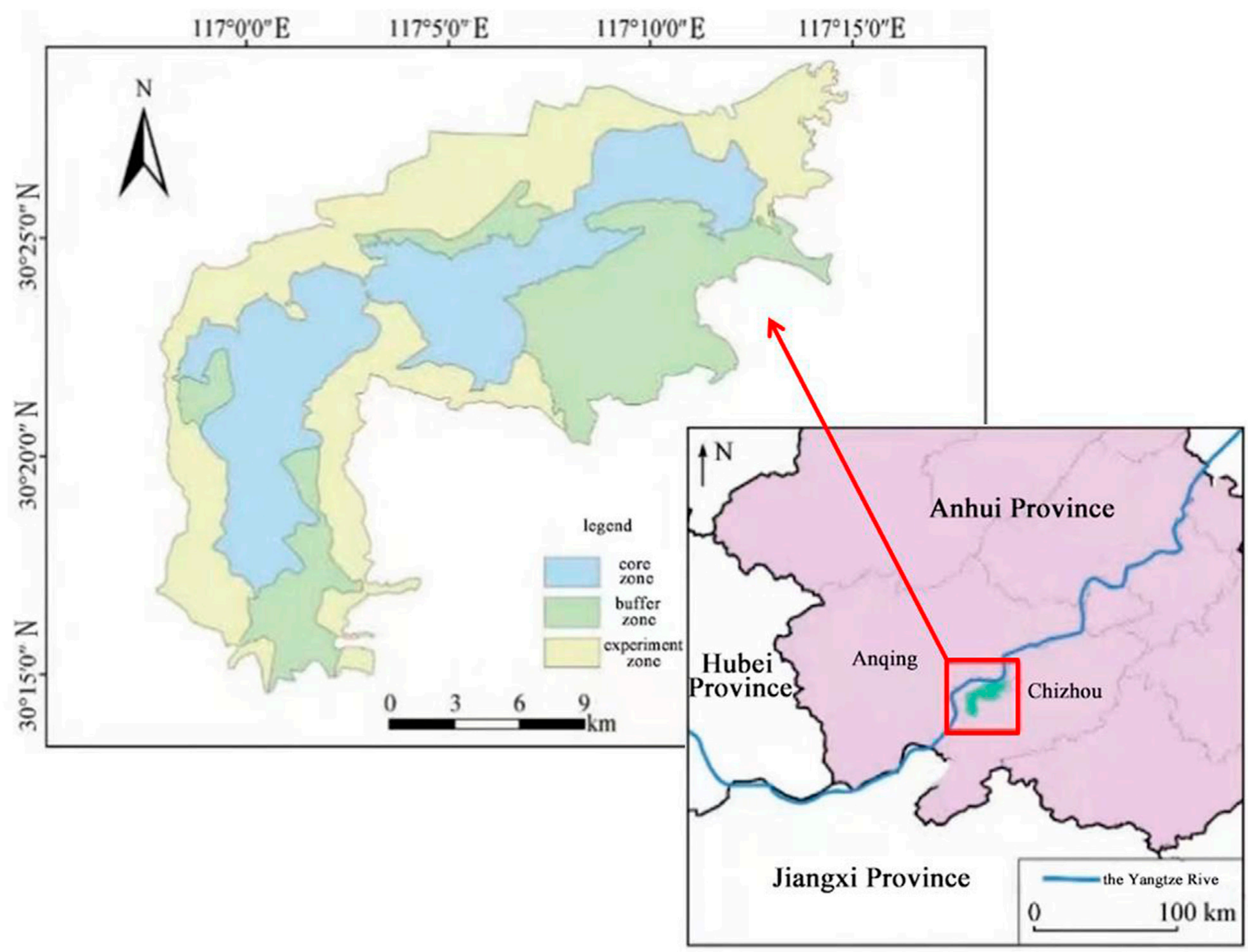

FIGURE 1
Location and function zones distribution of study site.

willingness to participate using the structural equation model (SEM). Feng et al. (2022) used the Giant Panda National Park in China as an example, and their qualitative study reflected that community governance and financial awareness have a positive effect on the willingness of residents to participate. The three main factors of TPB (attitude, subjective norms, and perceptual behavioral control) can also influence the willingness to participate (Jia et al., 2022). Furthermore, based on the extended TPB model, Zhao et al. (2022) added that the emotional factors of AWE and place attachment showed direct and mediating impacts on willingness, respectively. On the other hand, there has been a focus on the factors influencing actual behavior. Huber and Arnberger (2021) argued that the three main factors of the TPB significantly influence the level of local participation. In the context of eco-migration in China, Wang et al. (2020) examined the conservation behavior of local residents and reached a similar conclusion. Meanwhile, positive perceptions of PAs from community residents, according to Sirivongs and Tsuchiya (2012), significantly influence their participation. Additionally, socioeconomic factors also exert significant effects on participation behavior, including age, gender, occupation, years of residence in a community, household income, and expense (Smith, 2012; Belkayali et al., 2015; Apipoonyanon et al., 2019).

In conclusion, the topic of deviation between willingness and behavior has been explored. However, in terms of community participation, existing studies have mainly focused on the factors that influencing willingness or behavior separately. No studies have focused on the deviations between them. Hence, to fill this research gap and answer two questions mentioned above, a case study was conducted in a national nature reserve in Anhui Province, which is the main component of PAs in China (Jiang and Wu, 2021; Liu et al., 2022). First, this study aims to determine the deviation between willingness to participate and actual behavior in the management of PAs from community residents in the study area. Next, the logistic model is used to empirically analyze the factors that significantly influence the willingness-behavior deviation based on TPB. Finally, the Interpretative Structural Modeling Method (ISM) is used to clarify the hierarchical structure among these influencing factors and further analyze the internal mechanisms that affect the conversion from

TABLE 1 Distribution of the valid samples.

County	Town	Sample size	Proportion (%)	Village	Sample size	Proportion (%)	Function zone involved
Dongzhi	Shengli	46	23.35	Xinhua	21	10.66	buffer, experiment zone
				Jiangdong	25	12.69	buffer, experiment zone
	Dongliu	26	13.20	Jinshan	13	6.60	experiment zone
				Changling	13	6.60	buffer, experiment zone
	Zhangxi	31	15.74	Chentuan	16	8.12	buffer, experiment zone
				Bailian	15	7.61	buffer, experiment zone
	Dadukou	28	14.21	Xinfengwei	14	7.11	buffer, experiment zone
				Qingfeng	14	7.11	experiment zone
Guichi	Niutoushan	25	12.69	Niutoushan	14	7.11	experiment zone
				Mushan	11	5.58	experiment zone
	Tangtian	41	20.81	Wutian	20	10.15	buffer zone
				Shashan	21	10.66	buffer zone
Total		197	100	-	197	100	-

willingness to actual behavior. This study offers theoretical support and practical guidance for policymakers to formulate reasonable and effective measures to promote substantive community participation and sustainable development.

2 Materials and methods

2.1 Study site

The Shengjin Lake National Nature Reserve (SJLNNR), which is located in Chizhou City in Anhui Province in China, facing Anqing City across the Yangtze River, was chosen as the study site (Figure 1). It is located at the junction of Dongzhi County and Guichi District, covering a total area of 33,340 ha. Known as "China Crane Lake," SJLNNR is a representative wetland protected area that was established with the aim of protecting the freshwater wetland ecosystem and the rare and endangered waterfowl. Before the establishment of the SJLNNR, local residents closely relied on natural resources and supported themselves through agricultural cultivation, fishing and hunting. To achieve the protection goal of the SJLNNR, local residents are prohibited from catching fish in Shengjin Lake and hunting rare birds. In 2017, a total of 1,331 fishers stopped fishing, resettled, and went ashore to support themselves through other means. Meanwhile, the hunting of rare birds disappeared.

For better conservation, SJLNNR implements zoning control. It has been divided into core, buffer, and experiment zones, with areas of 10,150 ha, 10,300 ha, and 12,890 ha, respectively, accounting for 30.44%, 30.90%, and 38.66% of the total area of SJLNNR. The core zone is covered almost entirely by the lake and is under strict protection. In principle, all human activity is prohibited in the core zone, and no one is allowed to enter. The living areas of local residents in SJLNNR are mainly the buffer and experiment zones, involving 49 administrative villages in six towns (Shenli, Dongliu, Zhangxi, Dadukou, Niutoushan, and Tangtian), with a total population of approximately 64,200. Only scientific research containing no destructive influence is allowed in the buffer zone (Liu et al., 2022). In the experiment zone, multiple activities related to nature protection and sustainable development are permitted, such as scientific experiments, teaching practices, and ecotourism. In addition, crop farming and livestock breeding can only be conducted in the experiment zone. Currently, the agricultural population is approximately 22,000, whereas the rest mainly work away from their hometowns, especially young and middle-aged adults.

2.2 Data collection

The data used in this study were collected from survey questionnaires administered to community residents in SJLNNR. The field survey was conducted in January 2022 by three field workers, and a stratified random sampling method was used to select the respondents. First, two administrative villages were randomly selected from each town in SJLNNR (Table 1). Community residents were randomly selected, with the family considered as the unit from each administrative village. Upon arrival in each administrative village, field workers first visited village cadres who were chosen and organized to serve community residents. Accompanied by village cadres, field workers gained more trust from residents and successfully completed the questionnaire survey. They read the questions and then participants gave them answer verbally. All respondents voluntarily participated in this survey, and most were the main decision-making members of their families.

In this study, community participation was defined as the willingness and behavior of local community residents to improve the management and construction of SJLNNR. Actual participation referred to community residents taking action in SJLNNR management, and participation behaviors mainly

TABLE 2 Variable definition and descriptive statistics.

Variable name	Symbol	Variable meaning and assignment	Mean	Standard deviation	Index sources
Explained variables					
Deviation between willingness and behavior	y	Does the deviation exist between community residents' actual behaviors and their willingness to participate in the management of SJLNNR? Yes = 0, No = 1	0.32	0.468	Zhang et al. (2020a), Guo et al. (2021)
Explanatory variables					
Attitude(four variables)					
Awareness of the necessity of establishing SJLNNR	x_1	Do you think that the establishment of SJLNNR is necessary? Not necessary at all = 1, Not necessary = 2, Generally necessary = 3, Quite necessary = 4, Fully necessary = 5	4.25	0.923	Sirivongs and Tsuchiya (2012), Zhang and Li (2017)
Awareness of the importance of self-participation	x_2	Do you think that your self-participation is important for the successful conservation outcome of SJLNNR? Not important at all = 1, Not important = 2, Generally important = 3, Quite important = 4, Fully important = 5	4.05	0.973	
Understanding of environmental protection laws and regulations	x_3	Do you understand the environmental protection laws and regulations? Not understand at all = 1, Not understand = 2, Generally understand = 3, Quite understand = 4, Fully understand = 5	2.48	1.072	
Satisfaction with SJLNNR authority	x_4	Are you satisfied with SJLNNR authority? Not satisfied at all = 1, Not satisfied = 2, Generally satisfied = 3, Quite satisfied = 4, Fully satisfied = 5	3.36	1.511	
Subjective norms(two variables)					
Participation of important or recognizable people	x_5	Many important or recognizable people have participated in the management and construction of SJLNNR, such as decision-making, daily supervision and benefit sharing Strongly disagree = 1, Disagree = 2, No preference = 3, Agree = 4, Strongly agree = 5	1.59	1.109	Apipoonyanon et al. (2019), Li et al. (2021)
Technical training	x_6	Have you received technical training? Yes = 1, No = 0	0.11	0.309	
Perceived behavioral control(nine variables)					
Ecological knowledge	x_7	I have ecological knowledge Strongly disagree = 1, Disagree = 2, No preference = 3, Agree = 4, Strongly agree = 5	2.35	1.001	Sirivongs and Tsuchiya (2012), Zhang and Li (2017), Zhou et al. (2017), Gonçalves et al. (2021), Feng et al. (2022)
Government support	x_8	The government has supported the construction of SJLNNR. Strongly disagree = 1, Disagree = 2, No preference = 3, Agree = 4, Strongly agree = 5	2.12	1.394	

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TABLE 2 (*Continued*) Variable definition and descriptive statistics.

Variable name	Symbol	Variable meaning and assignment	Mean	Standard deviation	Index sources
Risk appetite	x_9	Risk aversion = 1, risk neutral = 2, risk preference = 3	1.60	0.747	
Future earnings expectations	x_{10}	I could get satisfactory earnings from SJLNNR in the future	2.76	0.947	
		Strongly disagree = 1, Disagree = 2, No preference = 3, Agree = 4, Strongly agree = 5			
Right to land proceeds	x_{11}	Do you retain the land proceeds right after the establishment of SJLNNR?	0.85	0.360	
		Yes = 1, No = 0			
Participation contents	x_{12}	I know what to do when participating in the management of SJLNNR.	1.98	1.147	
		Strongly disagree = 1, Disagree = 2, No preference = 3, Agree = 4, Strongly agree = 5			
Environmental improvement effect	x_{13}	SJLNNR has improved the surrounding environment of villages	4.00	1.105	
		Strongly disagree = 1, Disagree = 2, No preference = 3, Agree = 4, Strongly agree = 5			
Information	x_{14}	Do you know that the village committee has released related information on local participation in the management of SJLNNR?	0.65	0.477	
		Yes = 1, No = 0			
Ways to participation	x_{15}	Do you know how to participate in the management of SJLNNR?	1.48	0.726	
		No = 1, Unsure = 2, Yes = 3			
Individual and family characteristics (six variables)					
Age	x_{16}	Actual age	58.4	12.562	Zhang et al. (2020a), Li et al. (2021), Zhou et al. (2022)
Gender	x_{17}	Male = 1, Female = 2	1.26	0.439	
Education level	x_{18}	Primary school and below = 1, Junior high school = 2, Senior high school = 3, University and above = 4	1.85	0.955	
Resident members	x_{19}	Number of members living at home 6 months or more during the year per family	3.86	1.955	
Income	x_{20}	Average annual income per family	6.57	7.851	
Identity	x_{21}	Whether a village cadres or not: Yes = 1, No = 0	0.07	0.249	

included decision-making, benefit-sharing, and daily supervision. At the beginning of this survey, the meaning of community participation and specific participation actions were fully explained to the respondents by every fieldworker. The respondents were then asked two questions: 1) Are you willing to participate in the management and construction of SJLNNR? 2) Have you ever actually participated in? If they chose "yes," field workers would continue to ask about their specific willingness to participate or actual actions. If the answer was "no," field workers would also ask respondents about their understanding of participation in SJLNNR. Thus, whether these respondents understood the meaning of participation willingness and actual behavior could be determined according to their responses. If not, field workers would correct the variation in how respondents interpreted the meaning of "participation." During the survey, respondents could ask fieldworkers about technical terms in the questionnaire or other relevant questions at any time. Each questionnaire took 40 min to 1 h 200 questionnaires were distributed, and 197 were recovered, including 135 from Dongzhi County and 62 from Guichi District, with an effective rate of 98.50%. According to the total population in SJLNNR, the minimum sample size should be 100, at a confidence level of 95% and a precision level of 10% (Sarmah and Hazarika, 2012). A total of 197 valid questionnaires were collected, which was much greater than the minimum sample size.

2.3 Variable selection and descriptive statistics

The TPB was proposed by Ajzen et al. (1991), and was widely used to predict the willingness and behavior of an individual. According to the TPB, three main factors can directly influence behavioral intent: attitude, subjective norms, and perceived behavioral control. Behavioral intent, in turn, can directly determine the actual behavior of an individual (Ajzen, 1985) when the actual control conditions (e.g., individual capabilities, opportunities, resources) are sufficient. A deviation of behavior from willingness in individuals takes place owing to low facilitating conditions and intervening events (Gonçalves et al., 2021).Thus, the TPB connects individual willingness with behavior and provides theoretical support for the possibility of deviation between willingness and actual behavior of community residents in SJLNNR management.

Based on the TPB, attitude, subjective norms, and perceived behavioral control are the three dimensions that influence deviation in this study. In detail, attitude refers to the positive or negative evaluation of participation by community residents (Zhao et al., 2022); subjective norms refer to the external impetus and pressure caused by others when community residents make decisions on whether to participate (Jia et al., 2022); and perceived behavioral control refers to the perceived ease or difficulty based on personal control over resources, opportunities desires, and motives (Sultan et al., 2020) when community residents participate in the management of SJLNNR. In addition, relevant studies have also considered individual and family characteristics as potential influencing factors (Smith, 2012; Huber and Arnberger, 2021; Qiu et al., 2022). Therefore, this study analyzed the factors influencing deviation using four dimensions: attitude, subjective norms, perceived behavioral control, and individual and family characteristics. The deviation between participation willingness and the actual behavior of community residents in SJLNNR was taken as the explained variable, and its influencing factors were considered as explanatory variables.

From the descriptive statistics shown in Table 2, we can see that the average age of these community residents was approximately 58 years. Men and women accounted for approximately 74% and 26%, respectively, representing a large gap. This may be because the residents surveyed were mainly heads of households or family decision-makers, which were typically men in rural families in China. The education level of the samples generally reached that of junior high school. The average number of members living at home for six or more month during the year per family was four, and the average annual family income was approximately 65,700¥. Moreover, the proportion of village cadres was only approximately 7%.

2.4 Methods

As the explained variable (deviation between willingness and actual behavior) is dichotomous, a binary logistic regression model was used for the analysis. The logistic regression model was set as follows:

$$p_i = F(y_i) = \beta_0 + \sum\nolimits_{j=1}^{n} \beta_j X_{ij} = \frac{e^{\beta_0 + \sum_{j=1}^{n} \beta_j X_{ij}}}{1 + e^{\beta_0 + \sum_{j=1}^{n} \beta_j X_{ij}}} \tag{1}$$

where y_i is the deviation between the willingness and actual behavior of community residents in SJLNNR, defined as either 0 or 1, and X_{ij} denotes the value of the j^{th} variable of the i^{th} local resident. Furthermore, p_i is the probability of deviation, $F(y_i)$ is the probability distribution function, n is the number of explanatory variables, β_j is the regression coefficient of the j^{th} explanatory variable, and β_0 is the intercept. Next, we calculate logarithms on both sides of Eq. 1 to transform the non-linear relationship between the explained and explanatory variables into a linear relationship. The simplified form is as follows:

$$y_i = ln\left(\frac{p_i}{1 - p_i}\right) = \beta_0 + \sum\nolimits_{j=1}^{n} \beta_j X_{ij} \tag{2}$$

Based on Eq. 2, the probability of deviation between willingness and actual behavior to participate can be estimated, and the influencing factors can be further determined.

This study analyzes the hierarchical relationship among the influencing factors and discovers the direct, intermediate, and deep-rooted factors. The ISM was used to analyze the correlation between influencing factors. First, we determined the adjacency matrix R among the factors. It is assumed that the number of significant influencing factors is k, where S is used to denote the deviation between willingness and actual behavior and $S_i\,(S_j)\,(i, j = 1, 2, \cdots, k)$ is used to denote the factors affecting this deviation. The constituent elements of junction matrix R are defined as follows:

$$r_{ij} = \begin{cases} 1, & s_i\, is\, related\, to\, s_j \\ 0, & s_i\, isn't\, related\, to\, s_j \end{cases} \quad i = 0, 1, \cdots, k;\; j = 1, 2, \cdots, k. \tag{3}$$

TABLE 3 Willingness and actual behavior of respondents to participate in the management of SJLNNR.

		Willingness			
		Willing	Percentage	Unwilling	Percentage
Behavior	Participate	32	16.24%	0	—
	Not participate	133	67.52%	32	16.24%
Total		165	83.76%	32	16.24%

Note: total samples = 197.

TABLE 4 The results of sample data test.

Cronbach′s α					
Cronbach′s α			0.815		
KMO and Bartlett′s Test					
KMO				0.840	
Bartlett		Approx. Chi-Square		943.674	
		df		136	
		Sig		0.000	
VIF					
Variable	VIF	Variable	VIF	Variable	VIF
x_1	1.776	x_8	1.177	x_{15}	1.860
x_2	1.642	x_9	1.230	x_{16}	1.538
x_3	2.113	x_{10}	1.162	x_{17}	1.354
x_4	1.695	x_{11}	1.520	x_{18}	1.735
x_5	1.466	x_{12}	2.321	x_{19}	1.167
x_6	1.999	x_{13}	1.430	x_{20}	1.371
x_7	1.728	x_{14}	1.392	x_{21}	1.331
Hosmer-Lemeshow Test					
Approx. Chi-Square					11.894
df					8
Sig					0.156

Eq. 3 is used to determine the accessibility matrix M among the factors. The specific calculation formula for M is:

$$M = (R + I)^{\lambda+1} = (R + I)^{\lambda} \neq (R + I)^{\lambda-1} \neq \cdots \neq (R + I)^2 \neq (R + I) \quad (4)$$

where I is the identity matrix, $2 \leq \lambda \leq k$, and Boolean calculation is used for the power operation of the matrix. Next, we determine the level of influence of each factor. The basic calculation formula is as follows:

$$P(S_i) = \{S_i | m_{ij} = 1\}, Q(S_i) = \{S_i | m_{ji} = 1\} \quad (5)$$

$$L_1 = \{S_i | P(S_i) \cap Q(S_i) = P(S_i), i = 1, 2, \cdots, k\}. \quad (6)$$

According to Eq. 5, the accessibility matrix is divided into an accessibility set $P(S_i)$ and an antecedent set $Q(S_i)$, comprising the set of all factors that can be obtained from factor S_i in the accessibility matrix. Further, m_{ij} and m_{ji} both denote the factors in the accessibility matrix. The highest level L_1 and the influencing factors that L_1 contains are determined by Eq. 6; then, the other level factors are determined. The specific operation is that rows and columns of the most influencing factors are removed from the accessibility matrix M to form the accessibility matrix M_1, and the steps of Eqs 5, 6 are repeated to obtain the influencing level of the next factor, for all factors. Finally, a directed arrow is used to link the factors with the same level of influence and between adjacent levels.

3 Results

3.1 Deviation between willingness and actual behavior

As shown in Table 3, 83.76% of the respondents were willing to participate in SJLNNR management. In sharp contrast to the high willingness, only 16.24% of the respondents actually took actions. The willingness of community residents to participate did not fully translate into actual participation behavior. According to Rausch and Kopplin (2021), the deviation between willingness and actual behavior is generally divided into two different categories: 1) individuals that have willingness but no behavior and 2) individuals that have no willingness but behavior. In this study, 133 respondents expressed their willingness to participate but failed to perform actual behavior, accounting for approximately 67.52%. And these 133 respondents were considered for the following analysis. None of the respondents had no willingness but took action. Thus, a deviation exists between the willingness and actual behavior of local participation in SJLNNR, and there may be some factors that prevent willingness from completely converting into actual participation.

3.2 Regression analysis of the factors influencing the deviation

To ensure the reliability and validity of the empirical results, a sample data test must be conducted before using a binary logistic regression model. The test results are listed in Table 4, showing that the Cronbach's α is 0.815 and the KMO coefficient is 0.840 (which is close to 1), with $p < 0.05$. This indicates that the questionnaire has good reliability and validity, and it is suitable to continue with the factor analysis. The variance inflation factors (VIF) of all explanatory variables were less than five, indicating that there

10.3389/fenvs.2023.1062147

TABLE 5 Results of the logistic regression model.

Variable dimensions	Variable name	B	*p*-value	EXP B)
Attitude	Awareness of the necessity of establishing SJLNNR	0.792***	0.008	0.453
	Awareness of the importance of self-participation	0.321	0.259	0.725
	Understanding of environmental protection laws and regulations	−0.528*	0.060	1.696
	Satisfaction with SJLNNR authority	−0.328*	0.086	1.388
Subjective norms	Participation of important or recognizable people	−0.721***	0.008	2.057
	Technical training	−0.645	0.454	1.906
Perceived behavioral control	Ecological knowledge	0.191	0.505	0.826
	Government support	−0.173	0.389	1.189
	Risk appetite	−0.349	0.279	1.418
	Future earnings expectations	−0.599**	0.030	1.820
	Right to land proceeds	−0.164	0.781	1.178
	Participation contents	0.139	0.617	0.870
	Environmental improvement effect	0.645***	0.008	0.525
	Information	0.650	0.187	0.522
	Ways to participation	−0.407	0.306	1.502
Individual and family characteristics	Age	−0.001	0.967	1.001
	Gender	−0.577	0.271	1.780
	Education level	0.161	0.611	0.851
	Resident members	−0.357***	0.003	1.429
	Income	0.116**	0.020	0.891
	Identity	23.461	0.998	0.000

Note: Total samples = 133.
*, ** and *** represent significance at 10%, 5% and 1% levels, respectively.

was no multicollinearity problem among the explanatory variables. The *p*-value of the Hosmer-Lemeshow test is 0.156, which suggests that the null hypothesis of "the observation data and regression model fit well" is accepted and the results given by the binary logistic regression model to be analyzed next could reflect the true relationship between the original variables.

Binary logistic regression analysis was carried out on the sample data using the SPSS 26.0 software. As shown in Table 5, eight influencing factors were identified from the four dimensions. The detailed results are as follows:

(1) Attitude: The awareness by community residents of the necessity of establishing SJLNNR has a significant positive impact on deviation at the 1% level. This means that the more necessary community residents think the establishment of SJLNNR is, the more likelihood there is of a deviation between their willingness to participate and actual behavior. Their understanding of environmental protection laws and regulations and their satisfaction with SJLNNR both negatively affected the deviation at the 10% level. Specifically, community residents who are more familiar with laws and regulations on environmental protection and are satisfied with the governance of the SJLNNR authority are more likely to convert their willingness into actual participation. Additionally, awareness of the importance of self-participation had no significant impact on deviation.

(2) Subjective norms: The participation of important or recognizable people is negatively correlated with deviation at the 1% level. This signifies that the more neighbors, relatives, friends, or other important people participate in the management of SJLNNR, the more likely community residents are to engage in actual participation behaviors. However, technical training (e.g., ecological cultivation technology, green pesticide application, and freshwater aquaculture technology) did not significantly influence deviation.

(3) Perceived behavioral control: Future earnings expectations have a significant negative effect on deviation at the 5% level. This indicates that if residents have better future earnings expectations from SJLNNR, they will usually tend to participate. The realization of environmental improvement effect is positively correlated with deviation at the 1% level. The more obvious the environmental improvement effect of SJLNNR is, the more difficult

A	A	A	A	A	A	A	A	S_0
A	A	A	A	A	A	A	S_1	
A	0	V	V	0	A	S_2		
0	0	V	V	V	S_3			
A	0	A	A	S_4				
A	A	A	S_5					
A	0	S_6						
V	S_7							
S_8								

FIGURE 2
The logical relationship of the eight influencing factors.

it is for community residents to convert their willingness into actual behaviors. In addition, the effects of the other seven variables were not significant, even at the 10% level.

(4) Individual and family characteristics: The number of members with long-term residence in SJLNNR per family negatively influenced the deviation at the 1% level. This shows that community residents are more likely to take action when they have more family members permanently living in the village. Income was positively correlated with the deviation at the 5% level. In detail, Residents with more annual family income are less likely to convert their willingness into behaviors. The other four variables have no significant impact on the deviation.

3.3 Hierarchical structure of these influencing factors

From the results of the logistic regression model, eight factors that significantly influence the deviation between the willingness and actual behaviors of community residents to participate in the management of SJLNNR can be extracted. S_0 denotes the deviation, and $S_1, S_2, \cdots, S_8$ denote the awareness of community residents of the necessity to establish SJLNNR, understanding of environmental protection laws and regulations, participation of important or recognizable people, future earnings expectations, satisfaction with SJLNNR authority, realization of environmental improvement effect, number of members living at home for 6 months or more during the year per family, and average annual family income. The logistic relationships of the eight factors were determined based on theoretical support and expert opinions. As shown in Figure 2, "V" indicates that row factors directly or indirectly affect column factors, "A" indicates that column factors directly or indirectly affect row factors, and "0" indicates that there is no direct or indirect relationship between row and column factors.

According to Figure 2 and Eq. 3, adjacency matrix R among the nine factors can be obtained as follows:

$$R = \begin{array}{c} S_0 \\ S_1 \\ S_2 \\ S_3 \\ S_4 \\ S_5 \\ S_6 \\ S_7 \\ S_8 \end{array} \begin{bmatrix} 0&0&0&0&0&0&0&0&0 \\ 1&0&0&0&0&0&0&0&0 \\ 1&1&0&0&0&1&1&0&0 \\ 1&1&1&0&1&1&1&0&0 \\ 1&1&0&0&0&0&0&0&0 \\ 1&1&0&0&1&0&0&0&0 \\ 1&1&0&0&1&1&0&0&0 \\ 1&1&0&0&0&1&0&0&1 \\ 1&1&1&0&1&1&1&0&0 \end{bmatrix}$$

Then, accessibility matrix M is calculated from adjacency matrix R, according to Eq. 4, using MATLAB software:

$$M = \begin{array}{c} S_0 \\ S_1 \\ S_2 \\ S_3 \\ S_4 \\ S_5 \\ S_6 \\ S_7 \\ S_8 \end{array} \begin{bmatrix} 1&0&0&0&0&0&0&0&0 \\ 1&1&0&0&0&0&0&0&0 \\ 1&1&1&0&1&1&1&0&0 \\ 1&1&1&1&1&1&1&0&0 \\ 1&1&0&0&1&0&0&0&0 \\ 1&1&0&0&1&1&0&0&0 \\ 1&1&0&0&1&1&1&0&0 \\ 1&1&1&0&1&1&1&1&1 \\ 1&1&1&0&1&1&1&0&1 \end{bmatrix}$$

Next, according to accessibility matrix M, Eqs 5, 6, this study obtains the highest-level element set, which is $L_1 = \{S_0\}$. Furthermore, the 2nd-8th level element set can be obtained in turn, which are $L_2 = \{S_1\}$, $L_3 = \{S_4\}$, $L_4 = \{S_5\}$, $L_5 = \{S_6\}$, $L_6 = \{S_2\}$, $L_7 = \{S_3, S_8\}$, and $L_8 = \{S_7\}$. Reordering the rows and columns of accessibility matrix M according to $L_1, L_2, \ldots, L_8$, backbone matrix N can be obtained as follows:

$$N = \begin{array}{c} S_0 \\ S_1 \\ S_4 \\ S_5 \\ S_6 \\ S_2 \\ S_3 \\ S_8 \\ S_7 \end{array} \begin{bmatrix} 1&0&0&0&0&0&0&0&0 \\ 1&1&0&0&0&0&0&0&0 \\ 1&1&1&0&0&0&0&0&0 \\ 1&1&1&1&0&0&0&0&0 \\ 1&1&1&1&1&0&0&0&0 \\ 1&1&1&1&1&1&0&0&0 \\ 1&1&1&1&1&1&1&0&0 \\ 1&1&1&1&1&1&0&1&0 \\ 1&1&1&1&1&1&1&0&1 \end{bmatrix}$$

Finally, from backbone matrix N, it can be concluded that these nine factors were divided into eight layers. According to established logical relationships, the factors at the same level and between adjacent levels are connected by directed edges, and the hierarchical structure and correlation among the eight factors can be determined.

As shown in Figure 3, the eight influencing factors are at different levels. Most importantly, the number of members living at home 6 months or more during the year per family is a deep-rooted influencing factor. Future earnings expectations from SJLNNR, satisfaction with SJLNNR authority, realization of environmental improvement effect of SJLNNR, understanding of environmental protection laws and regulations, participation of important or recognizable people, and average annual income per family are all intermediate indirect influencing factors. Awareness of the necessity of establishing SJLNNR by community residents is a direct influencing factor at the surface level. Furthermore, the deep-

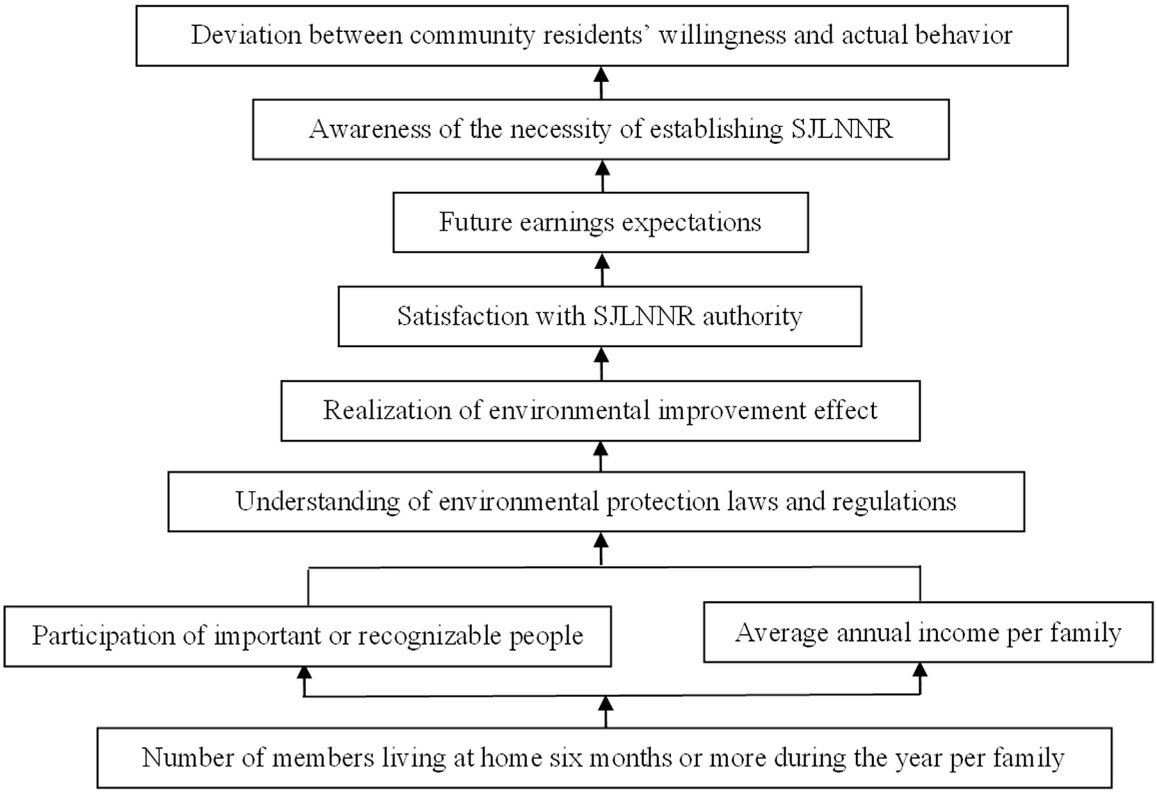

FIGURE 3
The hierarchical structure of the eight influencing factors.

rooted factor indirectly influences the deviation by affecting income and other six internal psychological factors.

4 Discussion

4.1 Influencing factors and practical reasons for the deviation

4.1.1 The lack of young and middle-aged adults is the root cause

The results from our study show that the number of resident members is a deep-rooted influencing factor that significantly decreases the deviation, which varies from the research finding of Zhou et al. (2022). This may be closely linked to the rural hollowing, which means that numerous educated young and middle-aged agricultural laborers in traditional agricultural areas transfer to non-agricultural sectors in urban areas during the process of rapid urbanization and industrialization in China (Cui et al., 2011). Rural hollowing is a widespread phenomenon throughout China and particularly exists in the area where SJLNNR is located. In addition, community residents have suffered economic loss owing to restrictions on the area of crop farming and livestock breeding since the establishment of SJLNNR. Coupled with the long-term fishing ban on Shengjin Lake, an increasing number of young and middle-aged adults in SJLNNR have left their hometowns to find jobs. Subsequently, the majority of permanent community residents in SJLNNR are elderly people and children, and the family structure consisting of grandparents and grandchildren is extremely common. However, elderly people and children are often unable to participate in the management of SJLNNR because of a lack of time, energy, knowledge, and poor health. Compared to these residents, young and middle-aged adults are more qualified to engage in actual participation (Espinoza-Cisneros and Akhter, 2020). Clearly, community participation can be promoted only when there are a sufficient number of young and middle-aged adults in SJLNNR. Thus, the lack of young and middle-aged adults is the root cause of this deviation. A higher number of members living at home with long-term residence per family means more young and middle-aged adults in SJLNNR, which in turn means a greater potential for effective community participation.

Furthermore, contrary to many previous studies on pro-environmental behavior (Sirivongs and Tsuchiya, 2012; Apipoonyanon et al., 2019; Lin and Shi, 2022; Ma et al., 2022), annual income per family was found to be a key factor that significantly increases the deviation in this study. This may also be related to rural hollowing and a lack of young and middle-aged adults. During the survey, we found that crop farming and livestock breeding could not guarantee self-sufficiency for most community residents in SJLNNR. Their family income is mainly from working outside. Families whose young and middle-aged adults work in non-agricultural sectors in urban areas always have higher annual incomes. In other words, higher annual family income means fewer young adults in SJLNNR, resulting in a deviation between willingness and actual behavior. Additionally, it can be seen that individual and family characteristics of community residents are fundamental driving forces for the occurrence of the deviation, which is aligned with several existing studies (Zhang et al., 2020a; Guo et al., 2021).

4.1.2 Inadequate ecological compensation is the direct trigger

Our study results indicate that the awareness by community residents of the necessity of establishing SJLNNR and the environmental improvement effect of SJLNNR are two factors that would both increase the deviation, which is different from previous research on pro-environmental behaviors (Vodouhê et al., 2010; Kuang and Lin, 2021; Li et al., 2021; Zhou et al., 2022), These unexpected results can be attributed to inadequate ecological compensation. During this survey, we found that the feelings of community residents regarding SJLNNR were complex. On the one hand, they agreed that SJLNNR plays an important role in nature protection and biodiversity conservation. After the establishment of SJLNNR, they could clearly sense the improvement in the local environment and the huge increase in wild animals, especially birds. On the other hand, they suffer economic loss from the growing number of wild animals, arising from such factors as crop destruction from wild birds and livestock injuries or deaths from other small mammals, whereby the relevant compensation is far less than the loss. They receive only 600 yuan per acre every year to mitigate the effects of crop damage from wild birds and barely receive any compensation for livestock deaths from wild animals. Some community residents regard SJLNNR as the cause of severe loss from wild animals (Ma et al., 2017). In other words, better environmental improvement means more wild animals, which in turn means more severe agricultural loss that cannot be compensated equivalently. Consequently, community residents tend not to engage in actual participation, and the deviation increases. Therefore, inadequate ecological compensation is the direct trigger for the deviation between willingness and actual participation in the management of SJLNNR. According to Ding and Qiu (2020), providing community residents with sufficient direct economic compensation may be effective.

4.1.3 Internal psychological factors significantly influence the deviation

Consistent with previous research on pro-environmental behaviors (Sultan et al., 2020; Eylering et al., 2022; Zhang et al., 2022), the results of this study also suggest that individual attitude significantly affects the deviation in behavior from willingness. Understanding of environmental protection laws and satisfaction with the SJLNNR authority are two factors that both have negative effects on the deviation. Clearly, if community residents understand environmental laws and regulations better, the concept of nature protection will be rooted in their hearts more deeply (Ding and Qiu, 2020), further promoting their conscious participation. As for their satisfaction with the SJLNNR authority, a possible reason is that the more satisfied residents are with SJLNNR, the more enthusiastic they are regarding community participation, leading to the conversion from willingness to actual behavior. As noted by Sirivongs and Tsuchiya (2012), higher satisfaction usually results in more positive participation in PA management.

Similarly, participation of important or recognizable people in the subjective norms dimension has a significant effect on the deviation. It has demonstrated to help achieve the consistency of participation willingness and actual behavior in this study, which is in line with an existing study by Guo et al. (2021). As community residents are widely affected by herd effect within the cultural context of “guanxi” which means relationship in Chinese, especially in rural areas (Wang et al., 2022), they tend to follow the crowd and make up their minds to participate in SJLNNR management under the pressure from others (Huber and Arnberger, 2021). Briefly, when relatives, neighbors, or friends make decisions regarding the formulation of reserve regulations, shared benefits from SJLNNR, or disclose activities with harmful influences on the environment, residents are more motivated to engage in actual participation.

Moreover, in the behavioral control dimension, future earnings expectations is also a key factor that has a significant effect on the deviation. Better future earnings expectations could decrease deviation. According to rational choice theory, community residents, as rational economically oriented people, often regard the maximization of their own interests as the basis for decision-making. If they predict that they could obtain satisfactory earnings from reserve employment, eco-tourism business, or reserve development projects and ecological projects carried out by the government or NGO in SJLNNR, they will be more active in engaging in the management and construction of SJLNNR (Dolisca et al., 2006). From the above analysis, it can be concluded that the internal psychological factors of community residents have a positive effect on the conversion from willingness to actual participation behavior.

4.2 Policy implications

Based on the above analysis, policy suggestions from three dimensions are proposed to decrease the deviation and promote the conversion of willingness to actual participation by community residents.

4.2.1 Local government

To realize SJLNNR community development, attracting young and middle-aged adults from urban areas to their hometowns is crucial. The best path may be to establish a variety of ecological industries and promote community residents to share satisfactory benefits from SJLNNR. First, the rational design and promotion of eco-tourism based on the natural landscape, wild animals, and local culture of SJLNNR should be conducted. Local governments should encourage community residents to manage eco-tourism businesses or to be employed to manage visitors, thus achieving alternative livelihoods. Second, actively cooperation with NGOs to carry out eco-friendly earning generation activities and projects (Sirivongs and Tsuchiya, 2012) should be undertaken to provide community residents with more economic benefits and job opportunities. Third, ecological agriculture and aquaculture should be developed, and the brand of SJLNNR should be established to enhance the value of eco-agricultural products. Local governments should actively introduce social enterprises to help community residents sell these ecological products, providing a certain proportion of funds per year to support community development.

Furthermore, an ecological compensation system needs to be developed. Local governments should scientifically formulate ecological compensation standards according to the opinions of relevant professionals to ensure that community residents receive commensurate economic compensation, particularly compensation for wildlife incidents (Ma et al., 2017). Besides direct economic compensation, local governments should prioritize local residents in SJLNNR when there are vacant positions related to nature protection, such as lake patrols.

4.2.2 SJLNNR authority

First, the authority should take the lead in establishing a co-management system, and fully respect the decision-making power of every community resident. When formulating natural resource protection policies and regulations, authorities should consult with representatives selected from community residents and listen to their opinions. Second, a mechanism for disseminating information should be established. Authorities should increase community-centered information communication channels and publicize the principles, policies and basic knowledge of SJLNNR to local communities through community organizations represented by village committees. Moreover, ensuring the right to know of the entire process of SJLNNR construction, operation, and management for the community residents would improve their trust and satisfaction with the authority. Third, an incentive mechanism must be established. The SJLNNR authority should set up a community reward fund to provide appropriate rewards and honorary certificates to communities or individuals who actively participate in and contribute to SJLNNR management to ensure the enthusiasm of community residents to perform actual participation behaviors.

4.2.3 Local community

To ensure the smooth participation of community residents in SJLNNR management, local community should improve the awareness of the residents and their ability to participate. First, the sense of ownership for each community resident should be cultivated. Through publicity and education, community residents would realize that they enjoy the right to manage SJLNNR; meanwhile, they would be responsible for participating in SJLNNR management. Second, the local community should actively cooperate with social environmental protection organizations and jointly carry out education and training for community residents, such as ecological cultivation technology, ecological breeding technology, and green pesticide application. In addition, an atmosphere should be created for everyone in this community to participate in the management of SJLNNR. Local communities should publicize the laws and regulations to community residents and encourage them to take the initiative to supervise and report illegal human activity in daily life, including fish poaching in Shengjin Lake, endangered-waterfowl poaching, and farming or breeding in the buffer zone. Moreover, human connections and the positive influence of relatives, neighbors, or friends who have actually participated in SJLNNR management should be employed, thus prompting community residents to take practical participation actions.

4.3 Limitations and research prospects

In this study, using the question "Have you ever participated in the management of SJLNNR?" to measure whether community residents have actual participation behaviors is relatively insufficient. To avoid the misinterpretation of the word "participation," we explained its specific meaning and provided examples to increase understanding during the survey. Future research could overcome this impediment by adding multiple-choice questions to the survey questionnaire, such as "What specific participation behavior have you ever had?" and list several types of participation behaviors for respondents to choose. Another limitation is that external contextual factors were not fully considered in this study, such as the types of jobs provided by SJLNNR, individual health status (Feng et al., 2022), and distance to Shenjing Lake (Qiu et al., 2022). In addition, future research can be extended to specific types of protected areas, such as wetland protected areas.

5 Conclusion

Community participation is important for effective PA management and long-term sustainability. To promote community participation, we explored the causes of the deviation between high participation willingness and low actual behavior, and suggested practical measures to decrease the deviation. Based on a field survey of SJLNNR in Anhui Province in China, this study applies Logistic-ISM to analyze the key factors influencing the deviation and further determine the logical hierarchy among these key factors. The results showed that eight factors had significant effects on the deviation. Among these, awareness of the necessity of establishing SJLNNR is a direct factor at the surface level, and participation of important or recognizable people, average annual family income, understanding of environmental protection laws and regulations, realization of environmental improvement effect, satisfaction with SJLNNR authority, and future earnings expectations are all intermediate indirect factors. Furthermore, resident member is a fundamental factor.

By linking these influencing factors and the reality of SJLNNR, we found that the lack of young and middle-aged adults is the root cause of the deviation, and inadequate ecological compensation is the direct trigger. Thus, attracting young and middle-aged adults to return to their hometown is the first step. In the context of rural revitalization in China, local governments should coordinate nature protection and community development and design a suitable sustainable development path for local residents. Establishing various ecological industries and creating a brand for SJLNNR may be good choices for achieving alternative livelihoods and developing local economies. Moreover, an effective ecological compensation system should be established to directly promote community participation. In addition, the internal psychological factors of community residents were found to significantly affect their actual participation behaviors. To decrease the deviation, the SJLNNR authority should improve the community participation mechanism, and local communities should enhance the awareness and ability of residents, and create an atmosphere for everyone to participate in the management of SJLNNR.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

TW: Formal analysis, methodology, investigation, software, writing–original draft, writing–review and editing. WJ: Funding acquisition, investigation, project administration, supervision. QW: Conceptualization, investigation, software, writing–original draft.

Funding

This study was funded by the Soft Science Project of National Forestry and Grassland Administration of China (2019131031).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 20 April 2023
DOI 10.3389/fenvs.2023.1132162

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OPEN ACCESS

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RECEIVED 26 December 2022
ACCEPTED 10 April 2023
PUBLISHED 20 April 2023

CITATION
Dias A, Robina-Ramírez R and Sánchez-Oro Sánchez M (2023), Territorial planning and sustainable development—case study: Protected areas in the territory of the Aspiring West Geopark, Portugal.
Front. Environ. Sci. 11:1132162.
doi: 10.3389/fenvs.2023.1132162

Territorial planning and sustainable development—case study: Protected areas in the territory of the Aspiring West Geopark, Portugal

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Introduction: The holistic concept of the sustainable development of United Nations Educational, Scientific and Cultural Organization (UNESCO) Global Geoparks encompasses the promotion of connected protected areas and activities that link geological heritage with other aspects of natural and cultural heritage. This case study aims to identify points of articulation and/or to identify conflicts in the overlap between protected areas and UNESCO World Geoparks in Portugal, and to provide information to improve the interrelation of these designations.

Methods: The methodological procedures in analysing the organisational structures of different classified areas from the respective management documents. The technical procedure consisted of document consultation and on-site activities carried out between September 2020 and November 2021.

Results: The study resulted in the identification of points of natural objects that can be held together by protected natural spaces and aspiring Oeste Geopark. A proposal for synergistic action was presented, with the main pillars of integration in the territory. The different designations for sustainable territorial management in complementary to the conservation of natural heritage. The results of the analyses indicate that the overlap of the different designations of areas and territories studied here can act both in a joint and complementary way to conserve natural heritage.

Discussion: This reinforcement study, which has different designations of areas and/or territories for sustainable territorial planning at the local, regional, national, and international levels, is fundamental for nature conservation, lacking more in terms of efficient management and integration of the social component.

KEYWORDS

heritage, conservation, management, nature, joint

1 Introduction

Territorial management is the challenge of a complex conservation of themes to reconcile the environment, which depends on environmental resources and environmental advances that are established in a territory, where they occur as diverse, close, and social developments as well as in disputes of the policies involved (Dong et al., 2021; Henrique and Toniolo, 2021; Li et al., 2022). The discussion has problems related to factors such as difficulty in socio-environmental processes and lack of development or interdisciplinarity, such as the involvement of society and nature (Li et al., 2022).

Thus, territorial planning must priorities a holistic approach (Duval and Benedetti, 2019) arising from territorial governance policies focused on environmental citizenship, going beyond sectorial ones (Sengur and Nurlu, 2021; Chaves and Barros, 2022). Governance with trans disciplinary and cross-sectoral actions is one of the mechanisms of increasing applicability ordered by the pillars of sustainability (Sengur and Nurlu, 2021; Chaves and Barros, 2022).

It is a biophysics strategy in which the biophysical and socioeconomic conditions and design needs of communities are present as solutions for development, as one must consider the traditional and ecological aspects committed to the sites (Altieri, 1995), surpassing only technological solutions devoid of culture and historical contexts (Pérez Rubio, 2007; Santos, 2015).

In this way, territorial planning and management are sustainable, develop a systemic approach, and are studied on an ecosystem basis (Castanho, 2017; Duval and Benedetti, 2019; Giraldo-Ospina and Zumbado-Morales, 2020). In this sense, protected areas and UNESCO Global Geoparks operate as tools to support territorial management (Canton, 2007; Sánchez Cortez, 2011; Pásková and Zelenka, 2018; Dong et al., 2021) as components that can participate in collaborative dialogue and strengthen their capacity to fulfill their role in the conservation of natural heritage.

As protected, both nationally and internationally, a relevant mechanism for the preservation and conservation of natural environments has been implemented for more than a century and half (Mora, 2009; Pellizzaro et al., 2015). Each country has a specific legislation for adjusting this mechanism and defining categories of protected areas (Pellizzaro et al., 2015). These are in line with international concepts, such as the "Washington Declaration" of 1940 and the International Union for Conservation of Nature (IUCN) concept, which was updated in 2008 (Mora, 2009).

The instruments for defining these areas, the Creation Law, and the Management Plan present rules and means for their use. Local creation and management are responsible for preserving the planet's biodiversity in the face of environmental degradation (Dudley, 2008; Pellizzaro et al., 2015).

Geoparks are attributed to the Global Geopark Network under the auspices of UNESCO to an area where geological heritage sites represent a part of the holistic concept of protection, education, and sustainable development (Medeiros et al., 2015; United Nations Organization for Education, Science and Culture [UNESCO], 2015). This brand was created in 2015, after almost two decades of the emergence of the Geopark concept (Pásková and Zelenka, 2018). Cooperation with the local population, one of the pillars of Geopark management, proves to be an effective strategy for the conservation of these sites (Henriques and Brilha, 2017), building a bottom-up process involving authorities, communities and private investors, as well as educational and research institutions (Farsani et al., 2010; UNESCO, 2010). The holistic concept of the sustainable development of UNESCO Global Geoparks encompasses the promotion of protected areas and activities that connect geological heritage with other aspects of natural and cultural heritage (UNESCO, 2015). It also emphasizes the need for a conservation model that encompasses the entire geographic and social environment, in addition to sites of biological interest (Sánchez Cortez et al., 2013). This is similar to other actors on a national and global scale (Melo Filho, 2021).

Of the 44 countries with geoparks, only 11 have 5 or more global geoparks. Portugal is among these countries (Setién, 2021). With 5 global geoparks and 3 aspiring projects Portugal has its relevance in terms of quantity and in relation to quantity per surface of the country. Since 2006, this country has been part of the UNESCO World Geoparks Network, providing experiences related to the involvement of local communities in the preservation of the natural heritage (Henriques and Tomaz C, 2012; Rodrigues et al., 2021).

The territory of the Oeste Geopark, aspiring to be the UNESCO World Geopark, is in the center-west region of Portugal (Figure 1), encompassing six municipalities, Bombarral, Cadaval, Caldas da Rainha, Lourinhã, Peniche, and Torres Vedras, with 212,103 inhabitants (Associação Geoparque Oeste [AGEO], 2021). It has a total area of 1,154 km^2, with 72 km of Atlantic coast where there are rocks with ages from the end of the Triassic to the Quaternary, mostly from the Jurassic (77%), Lower Cretaceous (13%), and other ages (10%) (Associação Geoparque Oeste, 2021).

The candidacy of this territory is justified by its diversified and historically relevant cultural heritage (material and immaterial) and the care of its natural heritage (Associação Geoparque Oeste, 2021). Historic site geodiversity is at the moment, of the record of a long history, portraying the gradual evolution of the Atlantic with 180 fossil fossils (vertebrates and invertebrates) inventoried until more than seven geosites were identified and characterised: a Global Boundary Stratotype Section and Ponto (GSSP of the Toarcian floor–Lower Jurassic), and extensive scientific publication on the geology of the region (Associação Geoparque Oeste, 2021).

Regarding biodiversity, the territory of the aGO is in the Mediterranean and Atlantic biogeographic regions, having distinct marine and comprehensive terrestrial ecosystems that extend from the Coastal Zone of the Western Region, passing through plateaus and wetlands to mountain range formations in the interior of the continent, comprising repositories of natural vegetation which are of national and international importance (Loureiro et al., 2007; Ferreira, 2013; Institute for the Conservation of Nature and Forests, 2020a).

The management accounts for local public entities and the integrated organizational partners of private entities, and local associations, at national and international levels. In this way, it carries out networking with the aim of encouraging the development of the region in accordance with the principles of protection and enhancement of natural and cultural heritage, research, and sustainable development (Associação Geoparque Oeste, 2021).

The UNESCO Global Geopark aspiring project overlaps with other internationally designated (the Biosphere Reserve and Ramsar Site) and protected areas instituted by legal mechanisms at the national level. Of the seventy geosite spaces identified so far, 34 were

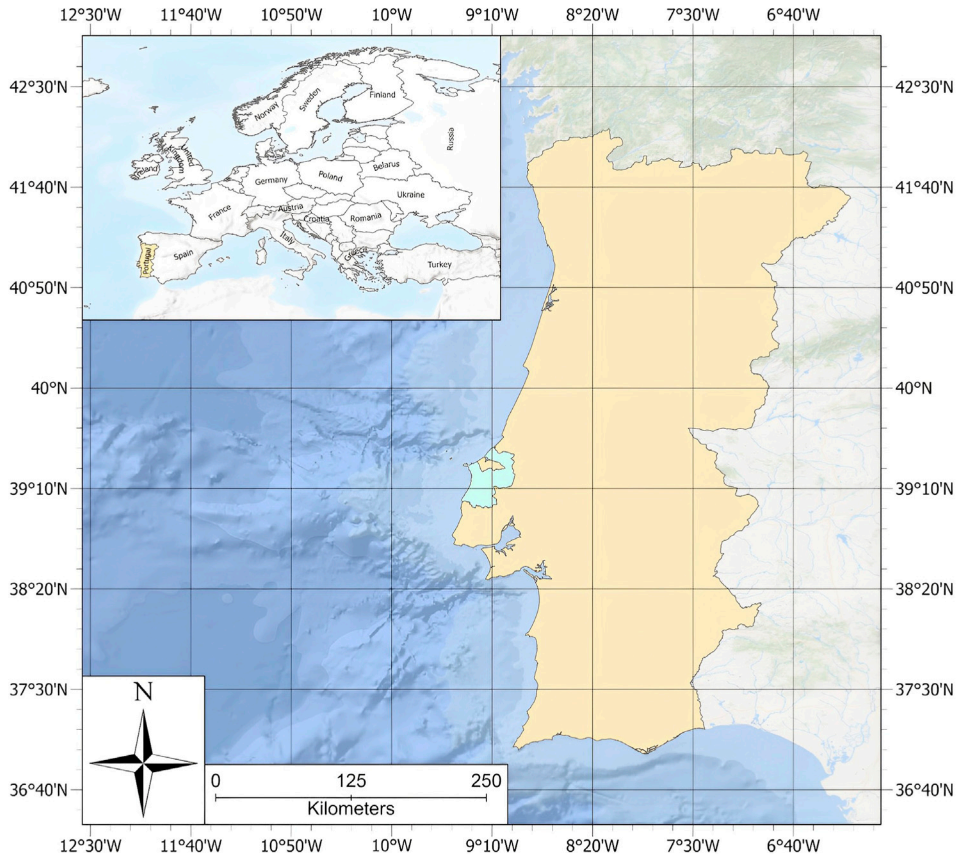

FIGURE 1
Location of the aspiring Oeste Geopark. Source: file made available by the aspiring Oeste Geopark team (2021).

in these protected spaces. With this configuration, aGO faces with the task of establishing partnerships with these areas, examining complementarity, building an independent brand, and publicizing them as protected areas (UNESCO, 2022).

This scenario evokes a comprehensive understanding of the importance of a conservation model for the synergy between geo diversity, biodiversity, culture, and tangible and intangible manifestations (Sánchez Cortez et al., 2013). Understanding the complexity of a territory with overlapping limits guides a more synchronized management that contributes to the fulfillment of conservation objectives (França and Martins, 2020).

This study addresses the issue of interaction between different designations of areas/territories that aim at sustainable territorial development. The research was developed at the institutional level with a document analysis based on the planning stage of activities with the local community and visitors.

The objectives of this study were to identify points of joint action and/or to identify conflicts in the overlap between protected areas and UNESCO World Geoparks in Portugal, and to improve the interrelation of these designations. In this study, the case of the aspiring Geoparque Oeste (aGO) and the protected areas included in this territory were chosen. It was considered because it is a project in the planning and preparation phase of the UNESCO World Geopark candidacy, which involves strategic collaboration with already established protected natural areas and those in the process of implementation. Furthermore, these areas represent different categories at national (local and regional), European and international levels.

2 Materials and methods

2.1 Study areas

In the territory of the aspirant Oeste Geopark, seven protected natural spaces are located, as shown in Figure 2.

The areas are marked by the National System of Classified Areas (SNAC) built by Decree-Law No. 142/2008 on 24 July (State of the environment report, 2021). Table 1 provides a description of these locations.

2.1.1 Areas designated by international commitments

2.1.1.1 Biosphere reserve (UNESCO)

A pioneer in the preservation of biodiversity, the Man and the Biosphere Program (MAB) was created 50 years ago (UNESCO, 2021). According to the ICNF Biosphere Reserve, this is a territory, where there is a mosaic of important and representative ecosystems of a given Biogeographic Region, whose purpose is to combine the conservation of

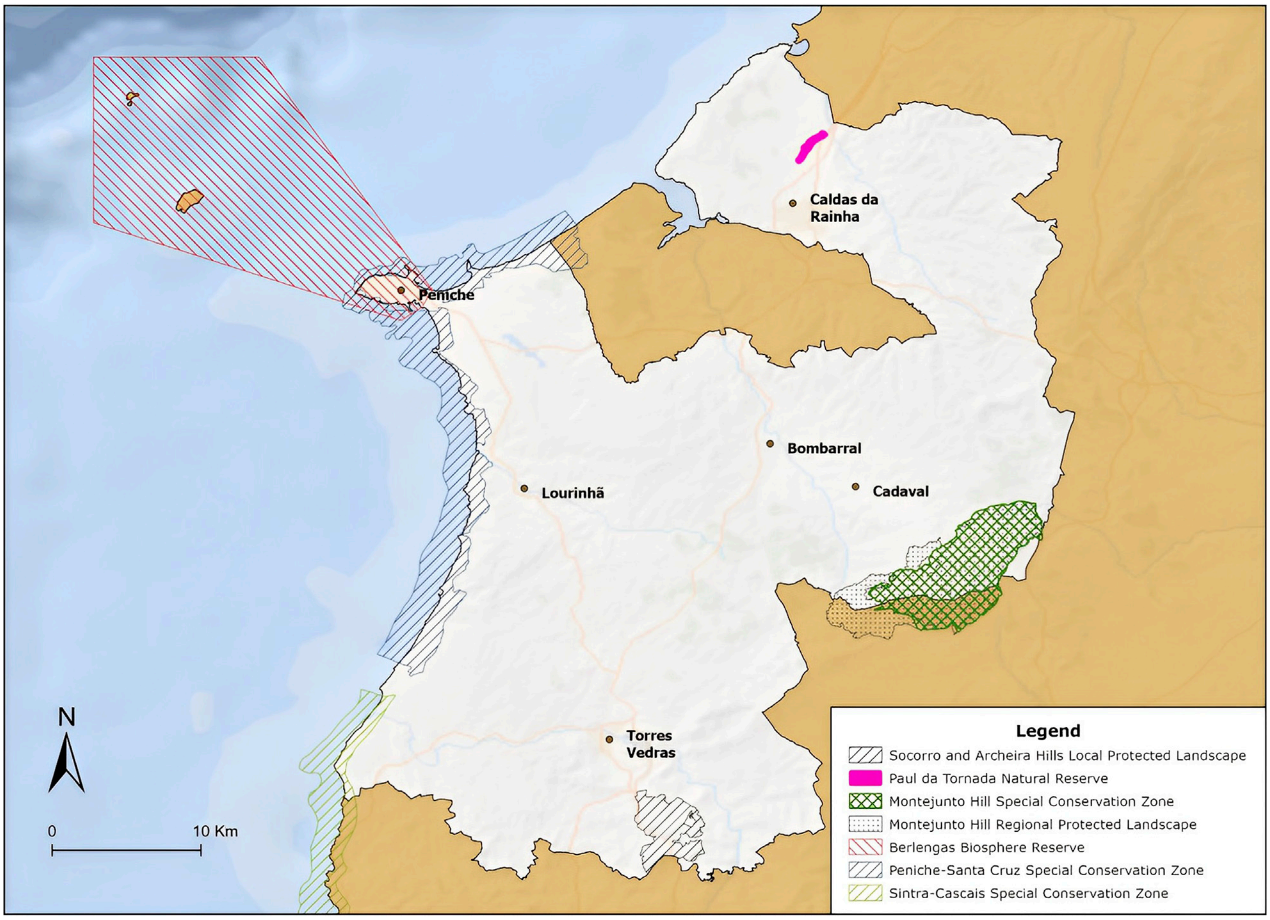

FIGURE 2
Protected natural spaces in the territory of the aspiring Oeste Geopark. Source: file made available by the aspiring Oeste Geopark team (2021).

natural values with the maintenance of cultural values and the sustainable socio-economic development of the population living in it.

The Biosphere Reserves integrate terrestrial, marine and coastal ecosystems. These are territories where interdisciplinary approaches are tested to understand and manage the changes and interactions of social and ecological systems, in particular conflict prevention and biodiversity management. Each Biosphere Reserve promotes the solutions appropriate to its reality with a view to reconciling the conservation of biodiversity with its sustainable use. They are places that provide local solutions to global challenges. The territories classified with this designation remain under the sovereign jurisdiction of the Member States where they are located. Its status is internationally recognized (UNESCO, 2021).

As a pilot area or sustainability laboratory, where innovation and knowledge transfer are promoted, Biosphere Reserves must necessarily promote 3 functions: 1) The conservation of species, ecosystems and landscapes; 2) Social, cultural and ecologically sustainable development; and 3) Research, monitoring, dissemination and environmental awareness (UNESCO, 2021).

As for zoning, they must present three types of interrelated areas that fulfill complementary functions and reinforce each other: core zone - one or more strictly protected areas dedicated to nature conservation, research and monitoring of less altered ecosystems; buffer zone - where the effects of human actions on the nuclear area are cushioned and where less impacting human activities are carried out, such as environmental education, recreation and leisure, nature tourism or applied research. It involves the nuclear zone; transition zone - a sufficiently large area where economic activities are developed and there are large population centers. It involves the buffer zone (UNESCO, 2021).

2.1.2 Berlengas-Peniche biosphere reserve

The Berlengas-Peniche Biosphere Reserve (Figure 3) was created in 2011 and covers an area of the current Berlengas Natural Reserve, Peniche Peninsula, and maritime corridor. Its management documents are the Management Plan for the Municipality of Peniche and the Management Plan for the Berlengas Nature Reserve, being managed by the ICNF (ICNB, 2007). Five geosites of aGO are located in the transition zone.

2.1.3 Ramsar convention

The Ramsar Convention is a global treaty that focuses specifically on wetlands. The Convention on Wetlands is an intergovernmental treaty that provides the framework for national action and international cooperation for the conservation and wise use of wetlands and their resources (Ramsar Site, 2021).

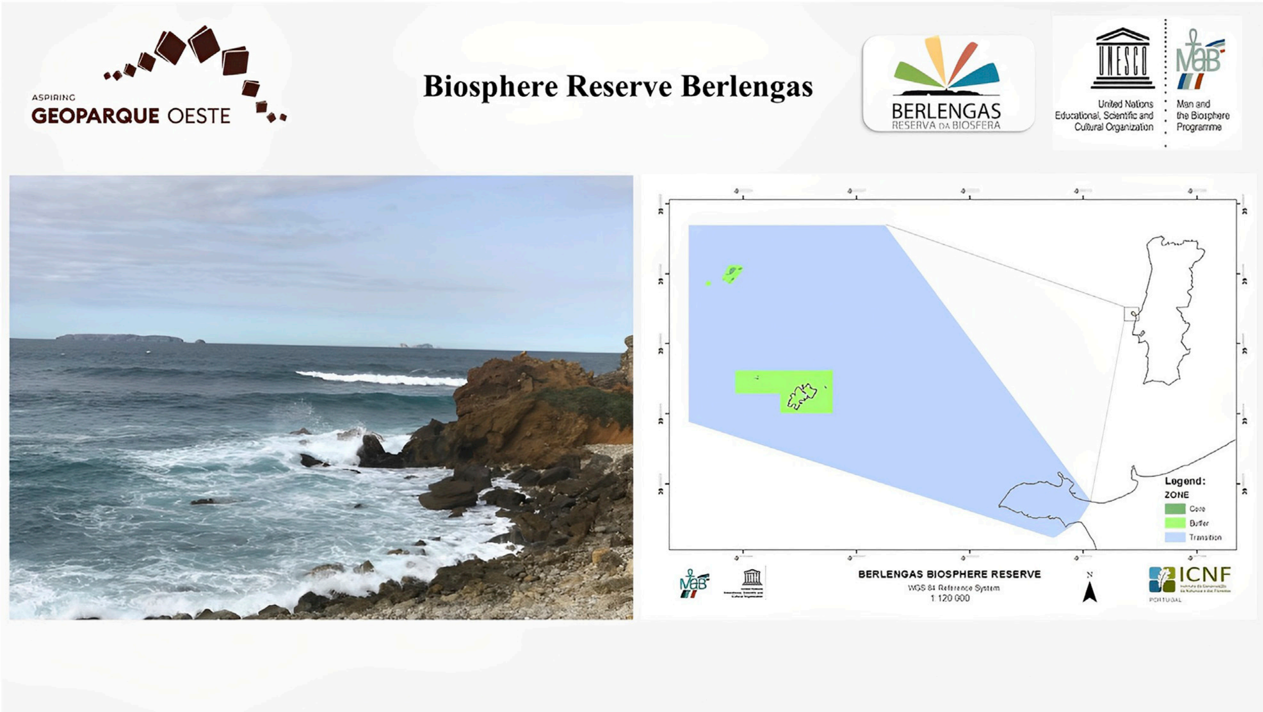

FIGURE 3
Berlengas-Peniche biosphere reserve. Source: produced by the authors.

2.1.4 Ramsar Paul da Tornada site

The Ramsar Site no. 1106 (Figure 4), called Paul de Tornada, superimposed on Paul da Tornada Local Natural Reserve, is located in the Municipality of Caldas da Rainha (Ramsar Site, 2021). Management at the international level takes place through the Strategic Plan for 2016—2024 (Ramsar Site, 2021). This is located at Geosite 1.

2.1.5 Natura 2000 (European Union)

2.1.5.1 Special conservation zones—ZEC (Natura 2000 Network)

Created under the Habitats Directive, with the express objective of "contributing to ensure Biodiversity, through the conservation of natural habitats and habitats of species of wild flora and fauna, considered threatened in the European Union." In these areas of community importance for the conservation of certain habitats and species, human activities must be compatible with the preservation of these values, aiming at sustainable management from an ecological, economic and social point of view.

2.1.5.2 Peniche-Santa Cruz special conservation area (PTCON0056)

Created in 2006, it extends along the coast as a strip of variable width (between 50 and 2,500 m) (Figure 5). The management documents are the Management Plan and Sectorial Plan of the Natura 2000 Network. The ICNF is the national management body here (ICNF b, 2020). There are 25 aGO geosites appearing in this zone.

2.1.5.3 Sintra-Cascais special conservation area (PTCON0008)

It is located in the Lisbon and Tagus Valley Region and mainly comprises the municipality of Sintra, also covering a useful area of the municipality of Cascais, and to a lesser extent, the municipalities of Mafra and Torres Vedras (Figure 6). The management documents are the April 2020 Update Plan and Natura 2000 Sector Plan. The ICNF is the national management body (ICNF, 2020c) and three geosites are located 3 here.

2.1.5.4 Serra de Montejunto special conservation area (PTCON0048)

It was created with the aim of protecting the natural habitats of the fauna and flora in the "Monte Junto" mountain range, which has high floristic diversity and calcicole Lusitanian endemism (Figure 7). Management by the ICNF takes place through the Sector Plan of the Natura 200 Network. These overlap with the Serra de Montejunto Regional Protected Landscape (ICNF, 2020d; ICNF, 2020e; Natura Network, 2021). Three geosites are located 3 here.

2.1.5.5 National Network of protected areas (Portugal)

At the national level in Portugal, Decree-Law No. 19/1993 of 23 January and established norms relating to the National Network of Protected Areas are followed. Derived from this regulation the Decree-Law No. 142/2008 of 15 July was amended, and republished by Decree-Law No. 242/2015 of 15 October that adds protected areas of regional/local scope (ICNF, 2020f). In Portugal, the classification "protected area" aims to grant a legal status of protection, at a national level, to the

TABLE 1 Areas designated for sustainable territorial management according to Portugal's national system of classified areas (nuclear areas) within the aGO territory. Source: Own elaboration.

Sustainable territorial management instrument	Level	Managing institution	Legal diploma/Regulatory mechanism/Conservation status		Typology	Denomination	Municipality(s)	Area (hectares) total	Area (hectares) aGO
International Commitments	International	ICNF[a]	UNESCO Man and the Biosphere - MAB" Programme/Portuguese Network of Biosphere Reserves		Biosphere Reserves (BR)	1. Berlengas-Peniche Biosphere Reserve**	Peniche	9,530	780.85
	International Conservation Programme UNESCO								
	European Union Biodiversity Management	European Commission/ ICNF	Natura 2000 Network		Special Conservation Zone (ZEC)	2. Peniche-Santa Cruz Special Area of Conservation	Peniche, Lourinhã, Torres Vedras	8,285.54	2,810.98
						3.Serra de Monte Junto Special Area of Conservation	Torres Vedras	16,631.88	404.29
			Directive 2009/147/EC/Directive 92/43/EEC			4. Special Area of Conservation Sintra-Cascais	Cadaval	3,830.49	2,836
Protected Area	National	City Council	Decree-Law No. 19/1993. Decree-Law No. 142/2008, as amended by Decree-Law No. 242/2015 of October 15	Regulatory Decree nº 11	Protected Landscape	5. Serra de Montejunto Regional Protected Landscape	Cadaval	4,897.45	3,374
				22 July 1999					
	National Protected Areas Network			Resolution of the Torres Vedras Municipal Assembly of 4 May 2012	Protected Landscape	6. Serras do Socorro e Archeira Local Protected Landscape	Torres Vedras	1,191.02	1,191.02
				Resolution of the Municipal Assembly of Caldas da Rainha	Natural reserve	7. Paul da Tornada Local Natural Reserve	Caldas da Rainha	53.65	53.65
International Commitments	RAMSAR Convention	ICNF			Ramsar site	7b. Paul da Tornada RAMSAR site	Caldas da Rainha	53.65	53.65

[a]ICNF, Institute for the Conservation of Nature and Forests (Portugal).

**The transition zone of the Berlengas-Peniche Biosphere Reserve overlaps with Nature corresponding to the delimitation of the aGO to the terrestrial part of the Municipality of Peniche (Institute for Conservation and Biodiversity [ICNB], 2007). Thus, it is declared that it does not belong to the aGO territory as "protected area" but as "classified area" related to the Berlengas archipelago: Berlengas Natural Reserve (Terrestrial), Berlengas Natural Reserve (Navy), and Special Protection Zone (ZPE Island Berlengas).

[1]Berlengas-Peniche Biosphere Reserve**

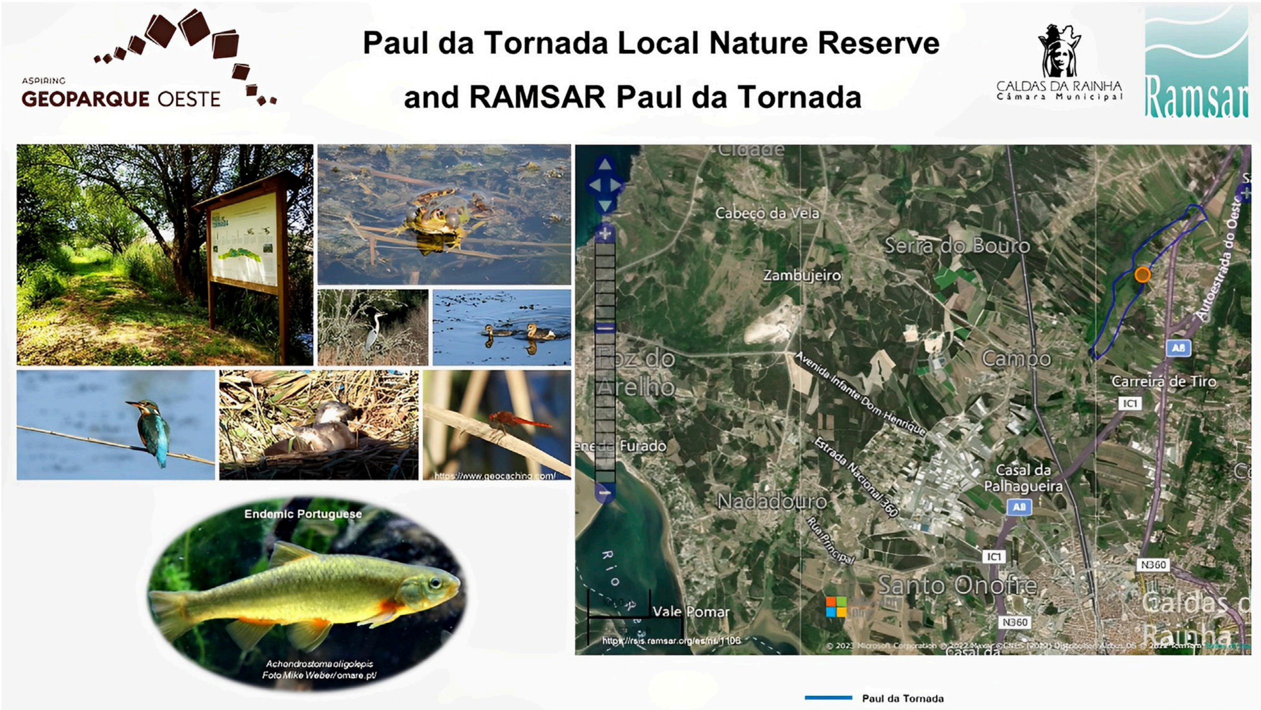

FIGURE 4
Ramsar Paul da Tornada site. Source: produced by the authors.

FIGURE 5
Peniche-Santa Cruz special conservation area. Source: produced by the authors.

FIGURE 6
Sintra-Cascais special conservation area. Source: produced by the authors.

FIGURE 7
Serra de Monte Junto special conservation area. Source: produced by the authors.

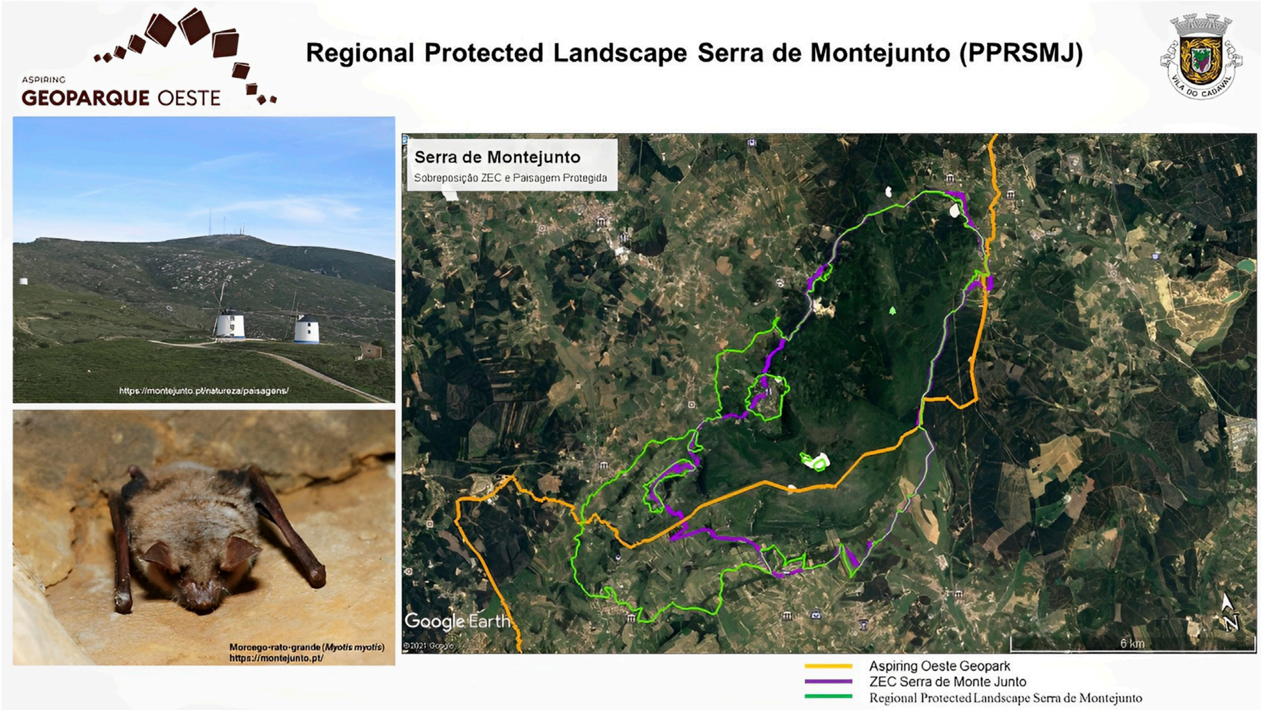

FIGURE 8
Serra de Montejunto regional protected landscape. Source: produced by the authors.

FIGURE 9
Serras do Socorroe e Archeira local protected landscape. Source: produced by the authors.

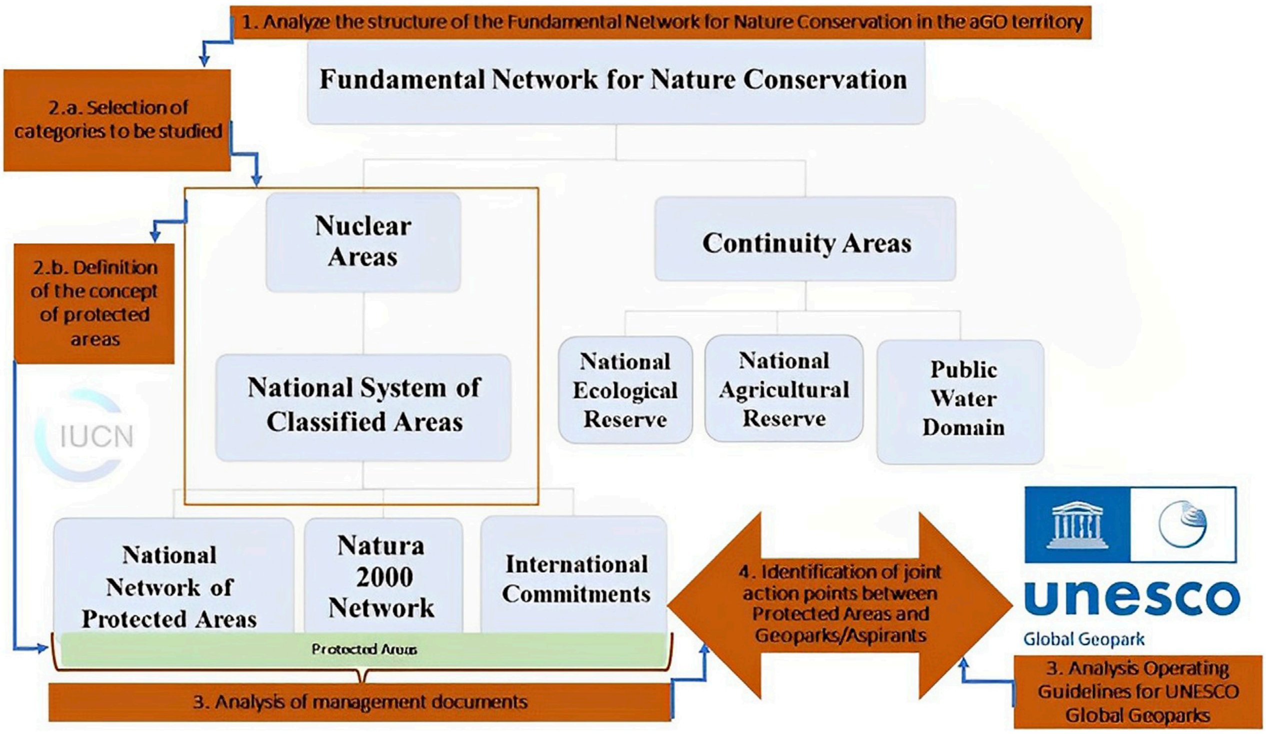

FIGURE 10
Research methodology. Source: elaboration based on Decree-Law No. 142/2008. On July 24, adapted by Nunes et al. (2016).

maintenance of biodiversity and ecosystem services and geological heritage, as well as the enhancement of the landscape (ICNF, 2020f).

2.1.5.6 Protected landscape

Areas containing landscapes resulting from the harmonious interaction of human beings and nature and which show great aesthetic, ecological or cultural value. 2 - The classification of a protected landscape aims to protect the existing natural and cultural values, enhancing the local identity, and the adoption of measures compatible with the objectives of its classification, namely: 1) The conservation of the elements of biodiversity in a context of enhancement the landscape; 2) The maintenance or recovery of landscape patterns and the ecological processes that underlie it, promoting traditional land use practices, construction methods and social and cultural events; 3) The promotion of initiatives that benefit the generation of benefits for local communities, from products or the provision of services.

2.1.5.7 Serra de Montejunto Regional Protected Landscape

Created in 1999, it has 4,897.45 ha (Ministry of the Environment, 1999) of which 3,830.49 ha correspond to the Serra de Montejunto Special Conservation Area (Figure 8). Management takes place through the planning plans of the municipalities in the area. They have managing bodies, such as City Councils, that integrate the area. 1 aGO geosite is located here.

2.1.5.8 Protected landscape of the Socorro and Archeira mountains

Created in 2015, it comprises the Serras do Socorro, Archeira, Galharda, and Monte Deixo (Figure 9). The Municipality of Torres Vedras is a management entity. The area does not have a Management Plan yet. Management tools include the Annual Monitoring Report and the “Landscape Observatory of the Local Protected Landscape of Serras do Socorro and Archeira” (Torres Vedras City Council, 2019). Here 2 aGO geosites are located.

2.1.5.9 Natural reserve

Natural reserve is defined as an area that contains ecological, geological and physiographic characteristics, or other types of attributes with scientific, ecological or educational value, and that are not permanently or significantly inhabited. 2 - The classification of a natural reserve aims to protect existing natural values, ensuring that future generations will have the opportunity to enjoy and understand the value of areas that have remained little altered by human activity during a prolonged period of time, and the adoption of measures compatible with the objectives of their classification, namely: 1) The execution of the necessary actions for the maintenance and recovery of species, habitats and geosites in a favorable state of conservation; 2) Conditioning visitation to a regime that guarantees minimum levels of disturbance to the natural environment; 3) Limiting the use of resources, ensuring the maintenance of the essential attributes and natural qualities of the area subject to classification.

2.1.5.10 Paul da Tornada local natural reserve

This is a wetland of approximately 53 ha, protected by the Ramsar Convention since 2013 (Figure 4). The area does not have an approved Management Plan for consultation. It is governed by the regulations of the Municipal Master Plan Charter. The area is managed locally by the

Municipality of Caldas da Rainha (Paul De Tornada Ecological Educational Center, 2021). 1 aGO geosite is located here.

2.2 Methodology

The present study is classified as descriptive and exploratory. Regarding the approach, the research is characterized as qualitative by analyzing the organizational structures of different classified areas from the respective management documents. The technical procedure consisted of document consultation and on-site activities carried out between September 2020 and November 2021, comprising the four steps described in Figure 10.

2.2.1 Analysis of the structure of the fundamental network for nature conservation in the aGO territory

The territorial designations of sustainable management were analyzed according to the definitions of the Fundamental Network for the Conservation of Nature of Portugal. Decree-Law n. o 142/2008, in its Article 5, creates the Fundamental Network for Nature Conservation, which includes categories already existing in the legislation, composed of nuclear areas (National System of Classified Areas: Protected Areas, Natura 2000 and Areas under international commitments) and continuity areas: National Ecological Reserve, REN; National Agricultural Reserve, RAN; and Public Water Domain (Nunes, 2016).

Additionally analysed were the kmz (Keyhole Markup language Zipped) format files of the delimitation of these areas, available on the ICNF geocatalago platform (ICNF, 2020g).

This stage allowed for the understanding of classifications, hierarchies, laws, and mechanisms of creation, delimitation, and overlaps, as well as the responsible management body directing the other stages of the research.

2.2.2 Selection of categories and definition of the concept of protected areas

Owing to the similarity of objectives and management mechanisms, this study considered all categories included in the subdivision “core areas”. Areas of continuity, areas of the private domain, and other designations of sustainable territorial management provided in Portuguese legislation, as well as other protection figures that do not have a legal regulatory mechanism, were not considered in this study.

For the definition of the term “protected areas” or “protected natural spaces,” this study considered the proposal by the International Union for Conservation of Nature in 2008, which denominates as “protected natural areas that are clearly defined, recognised, destined, and managed geographic spaces,” by legal means or other efficient alternatives, with the aim of conserving, in the long term, nature, ecosystem services and cultural values” (International Union for Conservation of Nature, 2020). Thus, in this case study, the term “protected areas” encompasses all areas included in the National System of Classified Areas in Portugal that comply with this definition, that is, the areas of the National Network of Protected Areas, Natura 2000, Biosphere Reserve and Ramsar Site.

2.2.3 Analysis of management documents

The organisational structures of areas designated for the protection and conservation of the natural heritage already established in the aGO territory was consulted.

The documents considered for this analysis were legal statutes for the creation of classified areas and other legislation relevant to the Fundamental Network for Nature Conservation, according to the legislation in force at Portugal: management data from the Institute for the Conservation of Nature and Forests (Portugal), legal statutes and Standard Data Forms of the European Environment Agency; Ramsar Convention Strategic Plan; and Operating Guidelines for UNESCO Global Geoparks. All of these are available for consultation on the respective websites.

Among the field activities, a meeting was held with members of the Torres Vedras City Council, responsible for the management of the Local Protected Landscape of Serras do Socorro and Archeiro, who presented the activities carried out in this protected area and described the possible points of joint action with aGO. Data on the management model, evaluation system, and indicators were sent via email. At this meeting, an interview was held with the following questions:

1. What is the structure and management model of the Serras do Socorro and Archeira protected area?
2. If the protected area has a Management Plan drawn up and approved;
3. What are the management indicators?
4. Which activities are developed with the participation of local communities?
5. What are the possible points of joint action/collaboration between the Serras do Socorro and Archeira protected area and a UNESCO Global Geopark?
6. Does the management group support the development of the project for the creation of a UNESCO Global Geopark in the territory?

The activities of the aGO team were also monitored regarding the establishment of formal partnerships with the managers of classified areas as well as the formulation of actions to promote, preserve, and conserve these spaces. A meeting was also held with the aGO team to characterise the areas of the Fundamental Network for Nature Conservation inserted in the applicant’s territory. At these two moments, participants’ considerations were collected on joint actions and the promotion of protected areas.

2.2.4 Identification of joint action points between protected areas and Geoparks/aspirants

Classified Areas in the public domain were analysed in terms of 1) Goals; 2) Management model and managing body, and 3) Objectives aligned with the proposal of the aspiring Oeste Geopark according to the criteria of the UNESCO Earth Sciences and Geoparks Program. A list of all the objectives of each of the studied protected areas was created in the same table. These objectives were compared with 12 criteria of UNESCO World Geoparks and Aspirants that include: 1) Geological Heritage Conservation; 2) Involvement with Natural Conservation; 3) Engagement with Cultural Conservation; 4) Education; 5) Research; 6) Geotourism; 7) Promotion of Natural Heritage; 8) Sustainable Development; 9) Participation of local communities; 10)

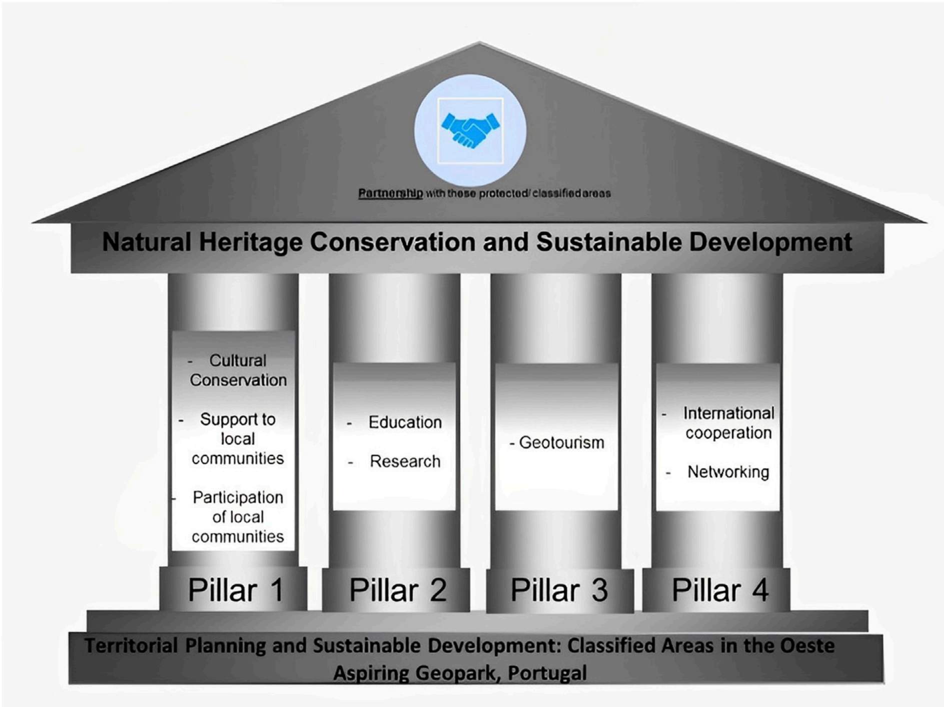

FIGURE 11
Pillars for joint action between classified areas in the aGO territory. Source: produced by the authors.

Support to local communities; 11) Networking; and 12) International Cooperation. These criteria were obtained from the UNESCO Statutes of the International Program of Earth Sciences and Geoparks.

For each objective of the areas classified in line with UNESCO criteria, one point was assigned so that the total score allowed the identification of the pillars of joint actions and how each UNESCO criterion appeared in the management documents of protected areas, portraying convergence or divergence.

3 Results

When analysing the guiding objectives of each classified area correlated with the criteria that the UNESCO Geoparks and aspirants must meet, the synergistic performance of these protection figures was observed. The establishment of a partnership between the aspiring Geopark Oeste and the classified areas in its delimitation can directly or indirectly cover activities that meet these objectives and criteria. This is described in Supplementary Table S1.

The criteria Involvement with Natural Conservation (B) and Sustainable Development (H) permeated all the objectives of each of the analysed protected areas; therefore, they presented higher scores, outlining the main similarities and convergences between geoparks and protected areas.

Owing to the geomorphological characteristics of the territory, the Geological Heritage Conservation criterion A) is consistent with at least one objective in each of the seven protected areas, which have the conservation of the landscape and/or habitats linked to the geological heritage. Only the designation of the Ramsar Site does not present objectives directly related to geological heritage. Thus, this criterion is the second with the highest score, that is, in alignment for joint actions.

The criteria for the Promotion of Natural Heritage (G), Education (D), and participation of local communities (I) did not score in the categories of the Natura 2000 Network. These areas focus on the conservation of species and habitats and are aimed at the concept of integral protection. The other protected areas have, in their objectives, the dissemination and promotion of these spaces, assigning 11 points to criterion G, which is the third with the highest alignment.

The education criterion is included in objectives related to dissemination and impact reduction, totaling nine points. However, it appears clearly expressed only in one objective of the Paul da Tornada Local Natural Reserve "7a.2. promotion of environmental education activities as a presupposition of a more harmonious relationship between man and the environment"; an objective of the Berlengas-Peniche Biosphere Reserve "1.3. Research, monitoring, dissemination, and environmental awareness; and an objective of the Local Protected Landscape of Serras do Socorro and Archeiro "6.5. Develop educational and scientific practices for the definition and study of environmental, natural, and cultural values, with the active participation of local communities, with a view to harmonious and sustainable human development."

The participation of local communities (I), in addition to not being included in the objectives of the areas of the Natura 2000 Network, is also not expressly included in the objectives of the Serra de Montejunto Regional Protected Landscape. Totalling 9 points, this criterion stands out in the objectives of the Ramsar

Paul da Tornada Site, the Local Protected Landscape of Serras do Socorro, Archeiro, and the Berlengas-Peniche Biosphere Reserve.

The criteria for Involvement with Cultural Conservation (C), Geotourism (F), Research (E), Support for Local Communities (J), Networking (L), and International Cooperation M) scored less than five points, portraying gaps that diverge from the holistic concept of conservation of natural heritage. Consequently, the main aspects of improvements in the efficiency of territorial management may result from the implementation of the geopark designation in the region under study.

Engagement with Cultural Conservation (C) is pertinent to the objectives of the Berlengas-Peniche Biosphere Reserve and the Local Protected Landscape of Serras do Socorro and Archeiro. Geotourism (F) does not appear to be expressed in any of the objectives; however, given the geological relevance of tourism in the region, those that included actions for tourism were considered. Thus, this criterion is present in the objectives of the Berlengas-Peniche Biosphere Reserve, Serra de Montejunto Regional Protected Landscape, Serra do Socorro, Archeiro Local Protected Landscape, and Paul da Tornada Local Natural Reserve.

Criteria of Research (E), Support for local communities (J), Networking (L), International Cooperation (M) had the lowest scores in this analysis.

Research (E) and Support to local communities (J) are only considered in the objectives of the Berlengas-Peniche Biosphere Reserve, Local Protected Area of Serras do Socorro, Archeiro, and Ramsar Site Paul da Tornada. The Ramsar Sites Strategic Plan inserts scientific guidance as one of its goals (Goal 4) and considers participating in and supporting local communities in the efforts necessary to achieve Goal 2.

Networking (L) is present in all objectives of the Strategic Plan for Ramsar Sites and International Cooperation (M) in objectives 1 and 2. This document highlights partnerships at various levels, including local, national, and international, as well as between all Ramsar Network Sites, and shared equally, between these sites and local communities, institutions, NGOs, and various social actors.

In addition to the points of joint action identified in the document analysis, the record of evaluations and suggestions from the managing members of the Local Protected Landscape of Serras do Socorro and Archeiro and the aGO team indicated new points and reinforced others identified in the document analysis.

The actions to encourage geotourism and support local communities were indicated by the management team of the Local Protected Landscape of Serras do Socorro and Archeiro as the main points of cooperation that correspond to expectations and needs in relation to the joint work between the Local Protected Landscape of Serras do Socorro and Archeiro and aGO.

The members of the aGO team also indicated as possibilities for joint action in the technical and institutional support for the elaboration of Management Plans for protected areas that do not yet have them or have concluded their elaboration. Within the scope of technical support derived from UNESCO criteria for conservation and promotion of natural heritage, mutual training between the GO and protected areas is also on the list of activities.

Considering the above, the protected areas with the greatest similarity between UNESCO's objectives and criteria are the Berlengas-Peniche Biosphere Reserve and the Local Protected Landscape of Serras do Socorro and Archeiro. The Ramsar Paul da Tornada site shows greater convergence with UNESCO criteria in terms of networking and international cooperation. The areas of the Natura 2000 Network (Special Area of Conservation Peniche-Santa Cruz, Special Area of Conservation Sintra-Cascais, and Special Area of Conservation Serra de Monte Junto) present more disparities.

4 Discussion

The results of the analyses indicate that the overlap of the different designations of areas and territories studied here can act both in a joint and complementary way to conserve natural heritage.

Simultaneously, cohabitation requires action planning based on communication and joint work to avoid conflicts between the management of these spaces and confusion on the part of the community (Finke, 2013; Osipova et al., 2017).

Understanding the categories and objectives of the spaces studied guides the development of activities, extracting the advantages of each designation and inserting them into a common roadmap that achieves the conservation of natural heritage and sustainable development.

The protected areas established in this territory have a history of years carrying out nature conservation activities with positive results and notoriety with the local population and visitors. On the other hand, with the implementation of the aGO, the development of the criteria Involvement with Cultural Conservation (C), Geotourism (F), Research (E), Support for local communities (J), Networking (L) and International Cooperation (M) can promote integration in the territory and contribute to solving existing weaknesses in the system of protected areas.

A geopark is different from many existing parks and protected areas to add a change in the way the landscape is understood, bringing positive impacts on environmental and economic aspects by promoting the territory at an international level, and for developing educational and interpretive activities with the main objective of educating visitors and the community (Moreira et al., 2021).

This study justifies the proposal of a synergistic action that considers the development of the following criteria: Involvement with Cultural Conservation (C), Geotourism (F), Research (E), Support for local communities (J), Networking (L) and International Cooperation (M). For this reason, the establishment of partnerships between the aGO and the designations studied, in addition to having nature conservation and sustainable development as the main axes, must be supported by four pillars, as shown in Figure 11.

The first pillar directs actions that involve the local community, working for the conservation of cultural heritage, support local communities, and participation of these communities. Understanding changes in the landscape over time related to historical and cultural aspects can be a tool for environmental awareness (Cardoso, 2012) and the cultural relevance of geoheritage is widely recognised and can form environmental management strategies (Pijet-Migo'n and Migo'n, 2022). Likewise, the activities of geoparks to rescue and enhance local cultural values include components that carry out the process of internalizing and living the values in their personalities, associating themselves with the community, and developing a more prosperous community life where there is greater interest towards environmental and scientific issues (Budiastra et al., 2021).

Regarding the association between protected areas and geoparks, the involvement of the local community is influenced by the historical relationship between the government and local communities, perceptions of nature protection, and attitudes towards the economic gain of nature (Mammadova et al., 2022), elements that must be observed in the construction of pillar 1.

The second pillar emphasises scientific knowledge and its transfer to society at different levels of formal and informal education. In addition to the importance of scientific production, making it reach the communities is a challenge in several fields of knowledge. For environmental education, its full promotion has been made possible by the geoparks program, as there is the integration of local communities with the environment; thus, the mechanisms of environmental awareness of society and visitors to the area are intensified (Salvetti, 2020). In other words, the process of Environmental Education in protected areas should adopt models observed for geoparks (Bacci, 2015).

Environmental education, developed in Portuguese geoparks, seeks to maintain close and active relationships with schools, teachers, and students through educational programmes to support conservation goals (Bacci, 2015).

Protected areas at the European and national levels in Portugal (ICNF b), as well as UNESCO Biosphere Reserves and Geopark designations, must be operated based on scientific knowledge; therefore, they need close collaboration between local authorities and universities (Mammadova, 2021). In Japanese local communities, the integration of UNESCO Biosphere Reserves and Geoparks into the educational curriculum provides site-specific knowledge and functions as a learning platform to teach about the link between human and nature interaction for regional sustainable development, and needs to be worked together to avoid confusion about common goals (Mammadova, 2021).

In addition, environmental education also benefits from the association of geoparks with protected areas that are already established or that will be created in the future, as the latter already have a legal regiment that can facilitate procedures with regulatory bodies for the development of educational activities that are non-formal or can be included in school curricula (Salvetti, 2020).

The third pillar is geotourism, in which protected areas play a fundamental and relevant role in geoparks, reinforcing the need to strengthen partnerships in territories with overlaps. Geodiversity is the main source of support for the development of geotourism, and the existence of biodiversity and cultural diversity adds value to tourists and helps preserve it (Lee and Karimova, 2021; Wulung et al., 2021).

The promotion of geotourism through protected areas and popular natural attractions increases socioeconomic, cultural, and environmental knowledge and promotes actions carried out in a territory (Quesada-Román et al., 2022) and can be a valuable opportunity for community development locations with numerous benefits (Zafeiropoulos et al., 2021). The use of the local richness and diversity of Natural Parks in Portugal, both from a landscape and cultural perspective, can be a tourist resource that must be promoted in an integral way, adding value to this type of tourist experiences (Ferreira and Sanchez Martín, 2021).

The fourth pillar of joint action is international cooperation and networking. These two aspects promote the entire territory at an international level, contributing to scientific, technological, educational, and tourist development (Zouros, 2004). The establishment of partnerships benefits the territory for international recognition and prestige, as a marketing tool for the region that can promote the region to new visitors, as well as enable international partnerships in various fields (Moreira et al., 2021).

Therefore, these pillars can help in understanding the roles of each member of a partnership and their points of cooperation. Since multiple titles and overlaps of areas and territories can cause divergence in terms of objectives and management models, confusion in the identification system and pressure on public administration, communication, and coordination between the institutions and departments involved in management is essential (Finke, 2013; Osipova et al., 2017).

Overcoming the problem of overlapping protected area boundaries caused by overlapping multi-internationally designated areas and delimitation of scientifically protected areas have been of considerable importance in achieving efficient management of natural protected areas in Jiangshan, China (Gao et al., 2022). As a solution, a technical structure was proposed for the delimitation of natural reserves through an evaluation index system for the integration and optimisation of the reserves, resulting in guidelines on the delimitation of the perimeter and integration of these areas, including discussing the delimitation criteria and the possibility of modifying them for more satisfactory management, fulfilling the objective of conserving natural heritage.

For the areas of the National Network of Protected Areas of Portugal protected by specific law, the pillars of joint action presented in Figure 4 can direct the focus of the partnership with the aGO. This complementation is understood as positive because the UNESCO criteria can contribute to gaps in protected areas regarding the involvement of society, education, and research. The perspective of international cooperation can be an important driver for the promotion of protected areas as well as for tourism development.

The Natura 2000 Network focuses on biodiversity in the context of the conservation of habitats and species of fauna and flora. Despite the objectives of these areas having scored only three UNESCO criteria, since they are inserted in a territory of geological relevance, the conservation of habitats is consistent with the conservation of geological heritage. The aspects of community support and participation, presented in pillar 1, can be delicate in the areas of the Natura 2000 Network; however, overcoming these conflicts is also a demand in areas that are more oriented towards integral protection. They need to develop holistic and inclusive processes that consider multiple dimensions of conflict (Andonegi et al., 2021). This requires close collaboration of the scientific team with various social actors, who represent the perspectives confronted, as non-experts can often see problems and solutions that specialists do not perceive (Andonegi et al., 2021).

Thus, as in the areas of the National Network of Protected Areas in Portugal, it is recommended that Special Areas of Conservation develop the pillars proposed in this study. During the monitoring of the activities of the aGO team, the request for a partnership with the managing body, the ICNF, was registered through meetings and by sending an official document for signature and formalisation of the partnership through a protocol. This procedure is under analysis by the managing body.

As for the internationally designated areas (Ramsar Sites, World Heritage Sites, UNESCO Biosphere Reserve, and World Geoparks), the Ramsar Paul da Tornada Site and the Berlengas-Peniche Biosphere Reserve have scores that are common to almost all UNESCO criteria for geoparks and aspirants owing to the international character of these three designations. Although the purposes of BR and UNESCO Global Geoparks (UGGp) differ, one of the main purposes of these two programmes is the participation and involvement of local communities in economic activities for regional, economic, social, and environmental development, which are the three dimensions of sustainable development supported by UNESCO (Mammadova et al., 2022).

The Ramsar Sites Strategic Plan does not expressly address the conservation of geological heritage; however, it reinforces the importance of partnerships with local institutions for all its strategic objectives. In particular, Paul da Tornada presents a relationship with the geological aspects inserted in the scope of action of the aGO in its historical ecosystem composition. The complementarity of these designations is particularly positive in terms of international cooperation, providing visibility, and greater possibilities for financing its activities.

The methodological analysis adopted in this study allowed us to clarify the limits of the overlapping of the aGO on the Berlengas-Peniche Biosphere Reserve, directing the actions to the terrestrial part of the transition zone of the Reserve, that is, the Peniche Peninsula. The possibilities of joint actions in other areas of the reserve are not excluded here, especially regarding education and scientific research; however, actions with the local community are considered a priority according to the proposal of synergistic action and respective pillars in the present study. International cooperation and promotion of reserves are also priorities.

This harmonious relationship between different designations within a common territory agrees with other studies of multi-internationally designated areas (MIDAs). The case study of Jeju Island Autonomous Province, Republic of Korea (Clamote Rodrigues and Schaaf, 2016) contemplates the four distinct international designations and concludes that the multiple designations led to a high level of local awareness about the critical connections between environmental conservation and sustainability. Overcoming the challenges consisting of effective governance based on synergy between the different objectives of each area. Recommendations are also made for managers at the local level, for authorities and focal points at the national level, and for designating bodies at the international level. The pillars of the synergistic action proposed for the AGO territory is in line with these recommendations.

Thus, for the alignment between classified areas, the synergistic action proposal presented here denotes an approach regarding the understanding of space and the establishment of the relationship between territory and identity (Sánchez Cortez, 2011). The definition of landscape and territory can be complex and emblematic, as its meaning is loaded with symbolism and representations, both from the point of view of its subjective perception and its objective perception. Landscape design must therefore be holistic and multi-disciplinary, and can be analysed in its particularity as an external aspect of an area–the territory (Silva, 2018).

UNESCO criteria listed as gaps (cultural conservation, geotourism, research, support for local communities, networking, and international cooperation) are aspects of the human component which must be present in sustainable territorial management.

Thus, the work carried out by UNESCO Global Geoparks is important from a holistic point of view when considering local communities as creating a strong identity based on the connection with the natural aspects of the territory (Sánchez Cortez, 2011).

In addition to the geopark structure the Man and Biosphere (MAB) Programm contributes to sustainability science, this network became an embodiment of sustainability science, by implementing a use-inspired, transdisciplinary research and action program at the human–environment interface (Reed, 2019). UNESCO Programs and Chairs offer a list of actions directly within the objectives of sustainable development, allowing citizens an integrated understanding of their territory (Bergman et al., 2018). These sustainability principles can positively guide management towards the preservation of biodiversity.

This holistic, inclusive, and integrative conception of heritage has been the core of the most recent international doctrine in which the participation of the entire community that enjoys it is fundamental (Silva, 2018). Thus, we have the construction of an "environmental knowledge" which implies a deconstruction of disciplinary, simplifying, unitary knowledge. This is a permanent debate in the face of conceptual categories and ways of understanding the world, forming social actors responsible for natural heritage (Leff, 2009).

There are Protected Areas where this holistic concept has already been developed in their management. However, it is still one of the challenges for many of these natural spaces that have little or no structure for their actions. Therefore, the establishment of UNESCO World Geoparks can make a significant contribution.

Therefore, the "gaps" criteria must be the focus of joint action for the effective management of the territory. Other protection figures must also be considered in a synergistic relationship with aGO territories.

5 Conclusion

The different designations for sustainable territorial management present complementary actions that favour the conservation of natural heritage. No points of divergence were identified between the criteria of the UNESCO Geopark Program and the objectives of the classified areas already established in the territory of the present case study. Such complementarity is already obvious from the different aspects of natural heritage (geodiversity and biodiversity) addressed in each designation. For the same reason that these aspects are intrinsic in nature, cooperation between these designations must be equally intrinsic.

Even though the Geoparks work more incipiently with local communities, the classified areas also envisage environmental education actions. Both mechanisms cooperate at different timescales, highlighting the importance of joint action in overlapping and/or bordering territories.

The aspects of geoparks concerning the active participation and appreciation of the local population in a concrete way and under a four-year evaluation can be an important factor for the conservation and preservation of natural heritage when considering the human component in an integrated way with nature.

Although protected areas have legal mechanisms established with clear rules of use and restrictions, they contribute to curbing the aggressive exploitation of natural resources. In this way, they can act on an emergency level, while the geoparks propose short-, medium-, and long-term result actions. The emergency nature of protected areas is fundamental, especially in countries where geodiversity and biodiversity are being rapidly destroyed. These protection figures represent advances in the conservation of natural heritage sites.

This case study reinforces that the different designations of areas and/or territories for sustainable territorial planning at local, regional, national, and international levels are fundamental to nature conservation, requiring more effort in terms of efficient management and integration of the social component.

For future research in this field, it would be useful to analyze other protection figures included in the Fundamental Network for Nature Conservation of Portugal (areas of continuity) and other mechanisms of this country, such as master and planning plans. As for the aGO, with the finalization of the strategic plan for this territory and approval of the candidacy for UNESCO's World Geopark, an assessment is recommended if these joint actions are being carried out. It is also necessary to produce more exhaustive analyses in different countries to improve knowledge about the joint action of protected areas and geoparks, as each country has its own legislation for protected areas.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

All the authors contributed substantially to this study. The task of the study conception and design, manuscript preparation and writing, as well as critical review was developed as a group. Author DA was especially responsible for conceptual and theoretical development, data acquisition, and technical procedures. RR and MS-OS were responsible for the data evaluation, interpretation, analysis, review, and editing.

Funding

This research received financial support from funds from the Erasmus + UEx Quercus Program (Proyecto 2019-1 ES01-KA103-061559).

Acknowledgments

The authors would like to thank Associação Geoparque Oeste (AGEO) for supporting this study.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2023.1132162/full#supplementary-material

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frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 30 May 2023
DOI 10.3389/fenvs.2023.1095321

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OPEN ACCESS

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RECEIVED 11 November 2022
ACCEPTED 02 May 2023
PUBLISHED 30 May 2023

CITATION
Song Y, Cheng Q, Gan X and Huang H (2023), The dual environmental and economic effects of the emission trading scheme under local fiscal pressure: "efficient markets" and "promising governments". *Front. Environ. Sci.* 11:1095321. doi: 10.3389/fenvs.2023.1095321

The dual environmental and economic effects of the emission trading scheme under local fiscal pressure: "efficient markets" and "promising governments"

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Compared with developed economies, China implements the Emission Trading Scheme (ETS) within a fundamentally distinct political-economic-institutional context. This study aims to investigate the internal mechanisms and external constraints of emission trading scheme in achieving the dual benefits of environmental preservation and economic advancement within the institutional context of fiscal decentralization. We demonstrate that the transmission from emission reduction to economic returns inherently facilitates the realization of dual benefits, and further propose a restrictive effect of local fiscal pressure on the effectiveness of the emission trading scheme. Using panel data of 284 prefectural-level cities from 2003 to 2017, we conduct a quasi-experiment based on China's emission trading scheme pilot policy in 2007. The results indicate three primary conclusions: First, the implementation of emission trading scheme in China generally yields dual environmental-economic benefits, with emission reduction serving as a transmission channel for realizing economic gains. Second, high fiscal pressure on local governments not only directly undermines policy effects but also indirectly affects the transmission channel. Finally, the dual benefits have been realized in eastern China, but not yet in the central and western regions. This study contributes to the research on market-oriented environmental governance under fiscal decentralization. The theoretical logic of this study can be applied to a wide range of market-based mechanisms for green factors trading, providing valuable insights for countries facing similar challenges.

KEYWORDS

emission trading scheme (ETS), local fiscal pressure, fiscal decentralization, regional heterogeneity analysis, transmission channels, fiscal constraint, dual environmental-economic effects, difference-in-differences (DID)

Abbreviations: ETS, Emission Trading Scheme; DID, difference-in-differences; IV, instrumental variables; SO_2, sulfur dioxide; NDRC, National Development and Reform Commission; GDP, gross domestic product; CGE, Computable General Equilibrium; NO_X, nitrogen oxide; IEADS, industrial enterprises above designated size; GRP, gross regional product; LGPBE, local general public budget expenditure; PSM, propensity score matching; GHG, greenhouse gases; TSLS, two-stage least squares; LIML, limited information maximum likelihood; GMM, generalized method of moments; IGMM, iterative generalized method of moments; CIEPD, China Industrial Enterprise Pollution Database.

1 Introduction

Traditional administrative-ordered environmental regulations have an immediate effect but impede enterprises' initiatives to reduce emissions, distorting market order (De Mulder, 2011). China is gradually shifting its environmental policies from administrative mandates to market-oriented ones, such as the Emission Trading Scheme (ETS) proposed by Dales (1968), which can effectively address environmental issues while simultaneously reducing the overall social costs of pollution control through market forces. However, it is still controversial whether the implementation of ETS in China can achieve dual benefits for both the environment and economy through "efficient markets."

Relying solely on market mechanisms to address environmental problems may encounter market failure due to the characteristics of public goods in the environment. Decentralized governments play a pivotal role in environmental governance (Oates, 2001). The evolutionary history of fiscal decentralization in China has resulted in a fiscal system that exhibits the characteristics of relatively low proportions of local revenue but high expenditure responsibilities (Bai et al., 2019), thereby engendering mounting fiscal pressures on local governments. Despite the abundance of literature on the relationship between fiscal decentralization and environmental governance, there is a lack of research exploring whether local fiscal pressures under fiscal decentralization pose a threat to market-based means of environmental governance, such as ETS. Compared with developed economies, China's implementation of ETS occurs within a completely different political-economic institutional context (Jiang et al., 2016). Fiscal decentralization represents an institutional arrangement that must be considered when evaluating the effectiveness of China's ETS policy.

This study aims to explore the internal mechanisms and external constraints of ETS in achieving dual benefits within the institutional context of fiscal decentralization. What is the interrelationship between the economic and environmental effects of ETS? How does this relationship facilitate the realization of dual environmental and economic benefits? Will local fiscal pressures under fiscal decentralization impede the effectiveness of ETS? To address these inquiries, drawing on the Porter hypothesis and property rights theory, we demonstrate that the transmission mechanism from emission reduction to economic return inherently fosters the realization of dual benefits. Furthermore, we propose a restrictive effect of local fiscal pressure on the effectiveness of ETS with the theoretical foundations in fiscal decentralization theory and Coase's second theorem.

Our first hypothesis posits that emission reduction serves as a transmission channel for realizing economic benefits within the ETS framework. The market-oriented ETS can stimulate enterprise innovation, and the resulting benefits of such innovation may offset or even surpass compliance costs associated with pollution treatment under the strong Porter hypothesis. In such circumstances, enterprises tend to promote their green production processes and reduce emissions to maximize profits. To theoretically validate our first hypothesis, we conduct a theoretical derivation from a micro-enterprise perspective. To empirically test this hypothesis, we take China's ETS pilot policy in 2007 as a quasi-experiment. Using panel data from 284 prefectural-level cities in China spanning from 2003 to 2017, we employ the difference-in-differences (DID) method to investigate the policy's effects on emission reduction and profit growth. Additionally, we incorporate a mediating effect model to examine an internal mechanism for dual benefits, that is, transmission from emission reduction to economic return. To alleviate the potential endogeneity of reverse causality between emission reduction and profit growth, we adopt two strategies: firstly, considering that future profits are unlikely to alter emissions generated in the past, we utilize industrial profits from the subsequent period instead of the current one as our dependent variable; secondly, we employ two instrumental variables (IVs), namely, the domestic garbage disposal rate and green space *per capita*, which can reflect a city's environmental management focus and commitment but are unlikely to impact industrial enterprise profits. Besides, we also employ staggered DID, Sobel test, and Bootstrap test to enhance the robustness of the mediating effect as much as possible.

Our second hypothesis posits that local fiscal pressure undermines the effectiveness of ETS, specifically including impacts on the environmental effect, the economic effect, and the transmission from emission reduction to profit promotion. Fiscal decentralization empowers local governments but also exacerbates their fiscal pressures, which curtails the financial expenditure of local governments to effectively manage emissions trading. When local governments under high fiscal pressure are captured by capital interests, potential rent-seeking corruption may affect excess emission fines and transaction costs (Fan et al., 2009). Furthermore, based on the theoretical derivation of Hypothesis 1, we illustrate how local fiscal pressure influences the economic effect and the transmission from emission reduction to profit promotion, specifically through the changes in initial quotas and excess emission fines. To empirically test this hypothesis, we use a triple-difference framework to examine the impact of local fiscal pressure on policy effectiveness. Additionally, we conduct grouped regressions separated by the median of fiscal pressure and further test differences in coefficients.

The results of this study offer three main conclusions. First, the implementation of ETS in China generally yields dual environmental-economic benefits and emission reduction is one transmission channel to realize economic benefits, implying a synergistic effect instead of a trade-off. Second, high fiscal pressure on local governments not only directly damages policy effects but also indirectly affects the transmission channel, which reveals the significance of a "promising government" in market-based environmental governance. Finally, the dual benefits have been realized in eastern China but not yet in the central and western regions, which can be explained by the constraint of fiscal pressure and the transmission efficiency from emission reductions to economic benefits.

The contributions of this article are mainly reflected in the following aspects:

First, from a novel perspective, we contextualize the evaluation of market-based environmental policies within China's fiscal decentralization system and investigate the dual environmental-economic effects of ETS under local fiscal pressure for the first time. Building upon the theoretical foundations of fiscal decentralization and Coase's second theorem, we propose that local fiscal pressure poses an external constraint on the effectiveness of ETS, thereby contributing to the literature on market-oriented environmental governance in a decentralized fiscal system. Distinguished from previous research that focused solely on the direct impact of administrative actions by local governments on the environment under fiscal decentralization, this paper emphasizes how to influence the operational effectiveness of ETS market mechanisms, revealing the significance of "promising governments" in market-based environmental governance.

Second, we demonstrate an internal mechanism of ETS to inherently promote dual benefits, that is, the transmission from emission reduction to economic return. Although policy evaluation of ETS has attracted wide attention, only a few studies discuss the dual environmental and economic effects of ETS and just separately examine the outcomes of the environment and economy. In fact, further elucidation of the interrelationship between environmental and economic effects is necessary to clarify how ETS achieves dual benefits. Our viewpoint is reinforced by Yu et al.'s (2022) study with micro-empirical evidence that the firms regulated by ETS improve the return on assets by cutting emissions. With the theoretical foundations in the Porter hypothesis and property rights theory, we theoretically deduce and demonstrate the transmission mechanism, which distinguishes our study from previous research.

Finally, this article offers two perspectives based on the theoretical hypotheses posited in this study to account for the regional variation in the policy effects: the impact of fiscal pressure and the conversion of emission reductions into economic benefits. Although regional heterogeneity analysis is common in policy evaluation, most articles merely describe the characteristics of regional differences but rarely explain the reasons. In contrast, we provide an account for the regional variation based on the theoretical hypotheses posited in this study. Methodologically, in addition to the grouped regressions based on regions adopted in previous studies, we employ a triple-difference model that incorporates regional dummy variables to examine heterogeneity. This approach can avoid identification interference caused by differences in control variable coefficients across groups.

While the policy focus of this paper lies on pollutant emission in China, the theoretical logic can be applied to a wide range of market-based mechanisms for green factors trading such as carbon emissions trading, energy use rights trading, and natural resources trading, which can effectively address issues related to climate change, energy scarcity, and natural resources' depletion. The reason for choosing the 2007 ETS pilot policy in this study is that it represents an earlier implementation of a green factor trading mechanism in China, thereby minimizing potential interference from subsequent policies. This study also provides valuable insights for countries facing similar challenges.

The remaining sections of this article are structured as follows: Section 2 introduces the background of the ETS policy and fiscal decentralization in China. Section 3 reviews relevant literature and presents the theoretical analysis. Section 4 describes the empirical strategy used in this study. Section 5 presents the results and discussion, including the dual environmental-economic effects of the policy and the inner link between them, the impact of fiscal pressure on the effectiveness of the policy, and regional heterogeneity analysis. Section 6 concludes and puts forward policy implications.

2 Background on China's ETS policy and fiscal decentralization

China initiated the sulfur dioxide (SO_2) ETS pilot policy in 2002. In 2007, Tianjin, Jiangsu, Zhejiang, Shanxi (a), Shanxi (b), Hubei, Hunan, Inner Mongolia, Hebei, Chongqing, and Henan were approved as ETS pilots. Subsequently, local governments successively introduced relevant policies. To standardize related management and further promote continuous and effective emission reductions, the State Council issued the "Guiding Opinions on Further Promoting the Pilot Work of Paid Use and Trading of Emission Rights[1]" (hereinafter referred to as Guiding Opinions) in 2014. The Ministry of Finance, together with the former Ministry of Environmental Protection and the National Development and Reform Commission (NDRC), issued the "Interim Measures for the Management of Revenue from the transfer of Pollutant Emission Rights[2]" in 2015. Currently, 28 provinces (autonomous regions or municipalities) have carried out the work of emission rights trading (Tibet, Guangxi, and Jilin have not yet begun). By the end of 2021, the total amount of paid use and trading of emission rights in China was 24.5 billion yuan. The transaction volume of pilot areas accounted for 83% of the total volume of the country, of which the secondary market contribution rate was 85%[3].

The evolutionary background of fiscal decentralization in China makes its fiscal system exhibit the characteristics of a relatively low proportion of local revenue but a high degree of expenditure responsibility (Bai et al., 2019). During the period of planned economy in China, with highly centralized finance, the central government bore a heavy burden while local governments lacked initiative and responsibility for over two decades since 1953. From 1980 to 1993, China underwent a transitional period from a planned economy to a free and open socialist market economy. To incentivize local government initiatives, China implemented the local financial package system during this time, which entrusts local governments with responsibility for annual budget utilization after central government approval. In 1994, the tax-sharing reform was implemented, which established a reasonable division of powers and responsibilities between central and local governments in terms of taxation. This resulted in a significant increase in the central government's share of fiscal revenue. In 2002, the income tax sharing reform further concentrated central finance revenue by shifting from territorial-based taxation to shared tax types between central and local governments (Xi et al., 2017). Hereafter, the highly centralized distribution of fiscal revenue, coupled with the "new normal" of slower economic growth in China, has impeded the growth rate of local fiscal revenue (Xia et al., 2022). Consequently, the conflict between limited funds for local fiscal revenue and rigid pressure on fiscal expenditure has

1 http://www.gov.cn/zhengce/content/2014-08/25/content_9050.htm (in Chinese).

2 http://www.gov.cn/zhengce/2016-05/25/content_5076588.htm (in Chinese).

3 https://www.eco.gov.cn/news_info/56610.html (in Chinese).

intensified (Bao and Guan, 2019), leading to increasing fiscal pressure on local governments.

3 Literature review and theoretical analysis

3.1 Literature review

3.1.1 Environmental regulation, ETS, and the dual benefits

In the traditional concept, environmental regulations impose additional costs on enterprises and potentially undermine economic growth, indicating a trade-off between the environment and the economy (Goodstein, 1996). However, the Porter hypothesis challenges the conventional wisdom by suggesting that well-designed environmental regulations, despite increasing costs, can stimulate innovation in enterprises to improve productivity and partially or completely offset compliance costs (Porter and van der Linde, 1995; Bosquet, 2000). It establishes a theoretical foundation for subsequent scholars to study the economic impacts of environmental regulations. Actually, Pearce. (1991) was the first to introduce the concept of a double dividend of the environmental tax policy, namely, pollution reduction and economic promotion.

ETS is an application of property rights theory to environmental problems (Coase, 1960), which internalizes externality problems generated by public products by establishing a market mechanism. The literature on evaluating the effects of ETS originally focused on the United States (US) and the European Union (EU) where SO_2 emissions trading and Carbon ETS were first implemented, respectively. Scholars have examined ETS from various perspectives, including abatement and environmental effect (Schleich and Betz, 2004; Anderson and Di Maria, 2011), cost-effectiveness and economic incentives (Rico, 1995; Neuhoff et al., 2006), the economic and environmental performances (Segura et al., 2018), etc. Nevertheless, the implementation of ETS in China differs from that in the US or EU in terms of market size and coverage, enforcement mechanisms and penalties, quota allocation, etc. (Yan et al., 2020). Studies on Chinese ETS policy are mainly conducted from three perspectives: (1) ex-ante analyses utilizing simulation models, such as the Computable General Equilibrium (CGE) model (Li et al., 2014; Cheng et al., 2016); (2) designs of trading mechanisms to enhance market liquidity and efficiency (Munnings et al., 2016; Zhao et al., 2016); (3) ex-post evaluation of policy effects using econometric methods (Xuan et al., 2020; Yan et al., 2020; Liu et al., 2021).

Scholars keep trying to verify whether ETS is a well-designed environmental regulatory tool supporting the Porter hypothesis (Jaffe and Palmer, 1997; Tang et al., 2020; Tan and Lin, 2022; Dechezleprêtre et al., 2023). However, empirical studies have yielded divergent conclusions regarding whether China's implementation of ETS has resulted in dual benefits for both the environment and the economy. Some studies cast doubt on achieving dual benefits from various perspectives, such as output promotion and employment increase (Hou et al., 2020; Zhang, 2020; Tan and Lin, 2022). Tan and Lin (2022) discovered that the carbon emission trading policy in China exhibits a discernible reduction effect on emissions, but an insignificant economic impact on output. They emphasized the necessity of external technological breakthroughs to achieve dual benefits. Hou et al. (2020) empirically tested that the policy was effective for regulating environmental pollution but ineffective for promoting the economy, utilizing gross domestic product (GDP) and *per capita* GDP as economic performance. Zhang (2020) concluded that the "blue dividend" (economic effect) was realized by significantly improving the employment level; however, no evidence of the "green dividend" (environmental effect) was discovered. Nevertheless, some empirical articles come to opposite conclusions. Ren et al. (2020) and Huang et al. (2021) identified the dual benefits of reducing SO_2 emissions while simultaneously increasing industrial output. Yang et al. (2020) empirically tested the double dividends of Carbon ETS in China, based on the economic outcomes of expanding employment. Yu et al. (2022) provided empirical evidence at the micro-enterprise level that China's carbon ETS reduces carbon intensity while improving return on assets.

3.1.2 Fiscal decentralization, local fiscal pressure, and environmental governance

As for whether fiscal decentralization contributes to environmental governance, the existing literature can be broadly categorized into three perspectives:

The first category of standpoint deems that fiscal decentralization fosters environmental governance (Oates, 2001; Jacobsen et al., 2012; Khan et al., 2021), and its theoretical underpinning is rooted in the first generation of fiscal decentralization theory. Decentralized governments play a crucial role in environmental governance by establishing and enforcing environmental standards and regulations (Oates, 2001). Local governments are typically better equipped to manage and enforce pollution control within their jurisdiction, and local pollution has implications for the allocation of expenditure and tax responsibilities across all levels of government (Alm and Banzhaf, 2012). Some scholars make explanations by the hypothesis of a "race to the top," that is, local governments compete to show their environmental governance performance by raising environmental standards and transferring pollutants to other areas to improve the environmental quality in their jurisdiction (Levinson, 2003; Khan et al., 2021).

The second kind of view, based on the second generation of fiscal decentralization theory, posits that fiscal decentralization is detrimental to environmental governance and aggravates environmental pollution (Sigman, 2005; Kunce and Shogren, 2007; Zhang et al., 2011; Deng and Xu, 2013; Huang, 2017; Khan et al., 2021). The decentralization-induced local competition may lead to inefficiencies in addressing practical environmental problems (Levinson, 2003), particularly in developing countries (Alm and Banzhaf, 2012). Based on the environmental externality hypothesis, decentralization may cause a "free rider" problem in local governments' environmental governance due to the cross-regional spillover effect of environmental pollution (Silva and Caplan, 1997). Contrary to the "race to the top" paradigm, the hypothesis of a "race to the bottom" suggests that local governments may lower environmental standards to attract enterprises and capital for economic development, which can lead to environmental degradation (Khan et al., 2021). Besides, some scholars argue that China's fiscal decentralization system makes the fiscal expenditure structure of local governments favor productive construction over public services (Fu and Zhang, 2007).

The third perspective emphasizes a nonlinear relationship between fiscal decentralization and environmental governance (Chen and

Chang, 2020; Cheng et al., 2020). Chen and Chang (2020) empirically tested an inverted U-shaped relationship between fiscal decentralization and pollutants in China. Cheng et al. (2020) explicated a nonlinear impact of fiscal decentralization on carbon emissions by examining various degrees of autonomy and levels of fiscal expenditure.

Although fiscal decentralization enhances the central government's macroeconomic control and fiscal flexibility, it also imposes significant fiscal pressure on local governments (Lin and Zhou, 2021). Bao and Guan (2019) pointed out that fiscal pressure undermined the environmental governance efficiency of local governments. Bai et al. (2019) discovered that fiscal pressure distorted tax competition among local governments, leading to the shielding of high-tax polluting enterprises by local governments to expand their tax base and increase revenue. Xi et al. (2017) illustrated this distortion from the perspective of changes in the composition of the value-added tax. Kou and Han (2021) observed that the positive impact of vertical environmental protection pressure on local environmental management was weakened by increasing local fiscal pressure.

3.1.3 Research gap

Prior literature offers us extensive experience and a foundational basis for study; however, there is still room for improvement and expansion in the following two aspects:

On one hand, although policy evaluation of ETS has garnered significant attention, only a limited number of studies have discussed the dual environmental and economic effects of ETS. These studies tend to separately examine the outcomes on the environment and economy to illustrate the respective benefits. To fully understand how the dual benefits are realized, it is crucial to further investigate the interrelation between environmental and economic effects. Yu et al. (2022) empirically tested that A-share listed firms regulated by ETS in China were able to improve their return on assets by cutting emissions. However, given the typically superior financial performance of listed firms compared to unlisted enterprises, there may be a risk of sample selection bias. Therefore, it is crucial to theoretically derive and demonstrate the transmission from emission reduction to economic returns.

On the other hand, in contrast to developed economies, China's implementation of ETS is situated within a fundamentally distinct political-economic-institutional context (Jiang et al., 2016). Fiscal decentralization represents a type of institutional arrangement. Although previous literature has already provided evidence of the relationship between fiscal decentralization and environmental governance, positive or negative, we have not yet found any article that combines ETS and fiscal decentralization to analyze the effects of market-oriented environmental regulations in the context of fiscal decentralization. Furthermore, while fiscal decentralization empowers local governments, it also exacerbates their fiscal pressures. However, just a few articles focus on local fiscal pressure under the decentralization system.

3.2 Theoretical analysis

3.2.1 The internal relationship of the dual effects

Figure 1 displays the analysis framework of this study.

According to the property rights theory (Coase, 1960), emission rights can be regarded as a special commodity granted by the government and traded among enterprises in a free market (Dales, 1968). Under a given emission quota, the costs of enterprises with higher emissions increase because of pollution treatment and the purchase of excess emission rights (Yu et al., 2020). In contrast, enterprises that emit less and protect the environment can realize economic benefits by selling or storing surplus emission rights (Ji et al., 2017; Narassimhan et al., 2018).

Based on the Porter hypothesis (Porter and van der Linde, 1995), environmental regulations can stimulate enterprise innovation, and the benefits of innovation may offset or even surpass the additional regulatory costs under the strong version of this hypothesis (Jaffe and Palmer, 1997). According to the narrow Porter hypothesis (Jaffe and Palmer, 1997), the market-oriented ETS is more likely to encourage enterprise innovation than command-and-control environmental regulations. Under an ETS, enterprises are motivated to optimize profits by promoting green production processes and reducing emissions (Yu et al., 2020).

To clearly illustrate the impacts of ETS on emissions and the economy, we conduct theoretical derivation from the micro-enterprise perspective. Enterprises can reduce emissions through a "scale effect" or a "technique effect." The former involves controlling the scale of production to generate fewer emissions, as pollutants are positively correlated with output (Jouvet et al., 2005). The latter comprises two kinds of technology: the "front-end technology" improves the efficiency of energy utilization, leading to less pollution during production at a given output level; the "tail-end technology" realizes a certain amount of decontamination after production but before emission (Dong and Yang, 2021).

In terms of the "front-end technology" for emissions reduction, referring to Zhang (2020), Eq. 1 represents the functional relationship between production-generated pollutants and output.

$$E = \frac{1}{t} \cdot z^{\sigma} \cdot Q \tag{1}$$

where Q denotes the level of output and E is the pollutants generated during production; z represents the production technology and σ reflects the emission ratio under the production technology z. t stands for the "front-end technology," with a range of $t > 1$; larger t is more conducive to emission reduction.

The "tail-end technology" will increase enterprises' additional expenditures for decontamination:

$$C_e(e_d) = \alpha e_d + \beta$$

where e_d is the amount of decontamination before emission and $C_e(e_d)$ represents the total costs to realize the amount of decontamination e_d; α and β stand for the unit variable decontamination cost and the fixed decontamination cost at a certain level of decontamination technology.

We categorize enterprises into two groups: enterprises whose actual emissions are below the quota (L enterprises) and enterprises that emit more than the quota (H enterprises). The two groups of enterprises produce identical products with equivalent structures of production cost $C_p(Q)$ (the same unit variable production cost a and fixed production cost b) and sell at the same price p. Several additional assumptions are made to exclude other interference[4].

4 Assumptions: (1) All enterprises own the same amount of emission quota e_0 (2). Equilibrium between production and marketing is obtained. Thus, all products manufactured can be sold out. Although production and sales levels can affect profits through changes in inventory cost, this article focuses on the impact of emission change on profits. (3) L enterprises sell surplus emission rights on the emission trading market, whereas H enterprises purchase excess emission permits. (4) Enterprises are rational economic agents pursuing maximized profits.

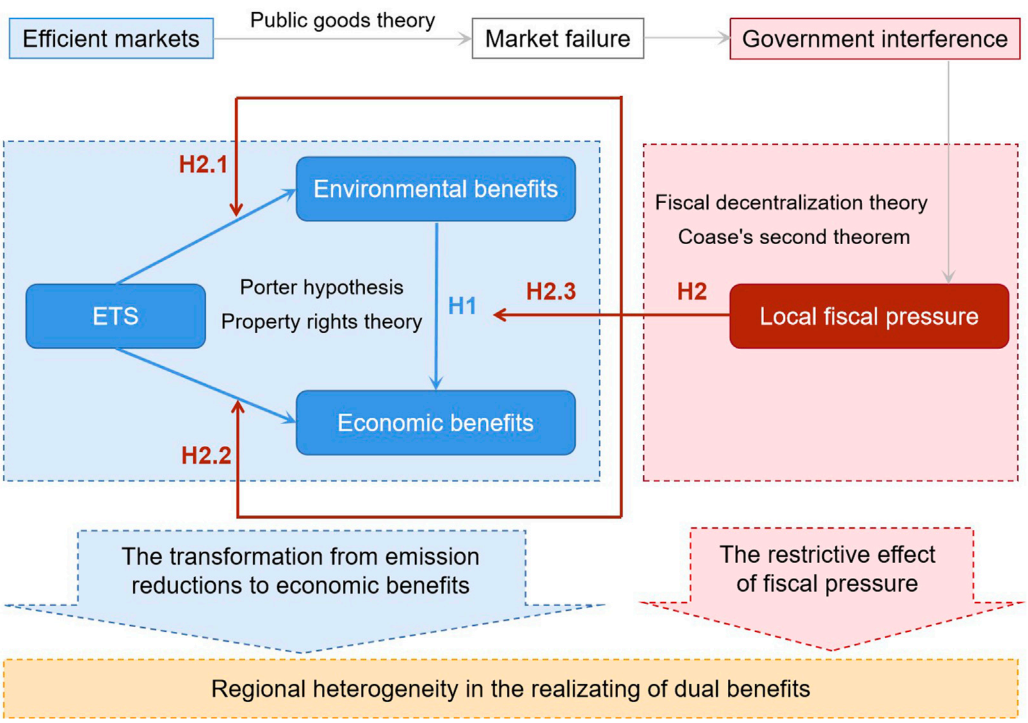

FIGURE 1
Analysis framework.

Eqs 2–5 denote the profits of the two enterprise categories before and after the ETS implementation, distinguished by subscripts. Although after the implementation of ETS, enterprises may adjust their technology level and cost structure, it is reasonable to assume that enterprises don't have enough time to adjust to the next stage in the short term.

$$\pi_L = pQ - C_p(Q) - C_{eL}(e_{dL}) = (p-a)Q - \alpha_L e_{dL} - \beta_L - b \quad (2)$$

$$\begin{aligned}\pi_{tradeL} &= pQ - C_p(Q) - C_{eL}(e_{dL}) + p_{trade}(e_0 - E + e_{dL})\\ &= \left(p - a - p_{trade}\cdot\frac{z_L^{\sigma_L}}{t_L}\right)Q + (p_{trade} - \alpha_L)e_{dL}\\ &\quad + p_{trade}\cdot e_0 - \beta_L - b\end{aligned} \quad (3)$$

$$\begin{aligned}\pi_H &= pQ - C_p(Q) - C_{eH}(e_{dH}) - F(E - e_{dH} - e_0)\\ &= \left(p - a - F\cdot\frac{z_H^{\sigma_H}}{t_H}\right)Q + (F - \alpha_H)e_{dH} + F\cdot e_0 - \beta_H - b\end{aligned} \quad (4)$$

$$\begin{aligned}\pi_{tradeH} &= pQ - C_p(Q) - C_{eH}(e_{dH}) - p_{trade}(E - e_{dH} - e_0)\\ &= \left(p - a - p_{trade}\cdot\frac{z_H^{\sigma_H}}{t_H}\right)Q + (p_{trade} - \alpha_H)e_{dH}\\ &\quad + p_{trade}\cdot e_0 - \beta_H - b\end{aligned} \quad (5)$$

where e_0, p_{trade}, and F denote emission quota, emissions trading price, and the fine for every unit of excess emissions, respectively.

To illustrate the effect of ETS on profits, we make Q satisfy the first-order condition of profit maximization and compare the differences in the maximum profits generated by enterprises before and after the implementation of ETS.

$$\begin{aligned}\frac{d\pi_L}{dQ} &= p - a = 0\\ \frac{d\pi_{tradeL}}{dQ} &= p - a - p_{trade}\cdot\frac{z_L^{\sigma_L}}{t_L} = 0\\ \pi^*_{tradeL} - \pi^*_L &= p_{trade}(e_0 + e_{dL})\end{aligned} \quad (6)$$

$$\begin{aligned}\frac{d\pi_H}{dQ} &= p - a - F\cdot\frac{z_H^{\sigma_H}}{t_H} = 0\\ \frac{d\pi_{tradeH}}{dQ} &= p - a - p_{trade}\cdot\frac{z_H^{\sigma_H}}{t_H} = 0\\ \pi^*_{tradeH} - \pi^*_H &= (p_{trade} - F)(e_{dH} + e_0)\end{aligned} \quad (7)$$

Definitely, $p_{trade}(e_0 + e_{dL}) > 0$ in Eq. 6. Therefore, we can infer that low-emissions enterprises earn more profits after the implementation of ETS, while the profits of high-emissions enterprises are not necessarily increased unless the trading price is higher than the unit fine.

To detect how enterprises' profits change in response to changes in emission reduction under the circumstance of emissions trading, we further take the derivative of maximum profits with respect to the amount of decontamination e_d. The differences in actual emissions between the two groups of enterprises are attributable to variations in the number of pollutants generated during production and the amount of decontamination. At a given level of output Q, E is determined. Therefore, what interests us is another factor determining the actual emission level, namely, e_d.

$$\frac{d\pi^*_{tradeL}}{de_{dL}} = \frac{(p_{trade} - \alpha_L)e_{dL} + p_{trade} \cdot e_0 - \beta_L - b}{de_{dL}} = p_{trade} - \alpha_L \quad (8)$$

$$\frac{d\pi^*_{tradeH}}{de_{dH}} = \frac{(p_{trade} - \alpha_H)e_{dH} + p_{trade} \cdot e_0 - \beta_H - b}{de_{dH}} = p_{trade} - \alpha_H \quad (9)$$

According to Eqs 8, 9, regardless of the actual emissions above or below the quota, the result of derivation is $p_{trade} - \alpha$. That means emission reduction can drive profit growth, provided that the emission trading price exceeds the unit variable decontamination cost. The latter (α) reflects an enterprise's technological level in reducing emissions, which is consistent with the Porter hypothesis.

To sum up, the implementation of ETS can result in increased profits for industrial enterprises with lower emissions. Furthermore, emission reduction efforts can drive profit growth for enterprises as long as the trading price exceeds their unit variable decontamination cost. Therefore, we propose our first hypothesis.

Hypothesis 1: ETS can promote industrial profits by reducing industrial emissions.

3.2.2 The impact of local fiscal pressure on the effectiveness of ETS

From a macro perspective of the entire society, cumulative social welfare is equal to the profits generated by all enterprises minus the losses caused by environmental pollution and regulatory and transactional costs. Coase's first theorem states that in a market with zero transaction costs, resources will be automatically allocated to the state of Pareto optimality by the market mechanism regardless of initial rights arrangements. Actually, due to factors such as information asymmetry, the transaction costs incurred by buyers and sellers are not negligible. As Coase's second theorem suggests, the initial allocation of legal rights can significantly impact resource allocation efficiency once transaction costs are taken into account (Coase, 1937). In this case, prohibitively high transaction costs result in the emitter's actual income being lower than its marginal cost of reducing emissions, which renders the ETS ineffective (Montero, 1998). It can be seen that the efficiency of ETS depends on factors such as initial allocation, transaction costs, and trading prices.

Apart from the fact that market forces essentially determine trading prices, neither the initial allocation nor transaction costs can get rid of government intervention. The initial quota is determined by the government based on supervision and audit, while institutional structures exert an impact on transaction costs. Fiscal decentralization, as an institutional arrangement, empowers local governments but also increases their fiscal pressure. When faced with mounting fiscal pressures, local governments may be more inclined to engage in a "race to the bottom" or experience a decline in their capacity for "racing to the top."

On one hand, fiscal pressure restricts the ability of local governments to manage emissions trading effectively, which means the capacity of "racing to the top" decreases. The ability of local governments to perform their duties affects the monitoring, accounting, and regulation of emissions, the quota allocation management in the trading market, and the reporting and disclosure of emissions by enterprises. Stable fiscal strength offers local governments the fund guarantee to fulfill their responsibility for environmental management (Liang and Langbein, 2015). Facing a substantial gap between fiscal revenue and expenditure, local governments have insufficient financial resources to provide regulatory staffing, materials and equipment, as well as support for environmental governance (Xi et al., 2017).

On the other hand, high levels of financial pressure force local governments to make a trade-off between economic development and environmental protection, which means the likelihood of "racing to the bottom" increases. Local governments under fiscal pressure may be vulnerable to capture by capital interests, resulting in rent-seeking corruption (Fan et al., 2009). Fiscally constrained governments may seek to close their fiscal gaps by selling emissions permits, which creates a fiscal externality in the permit market (Andersen and Greaker, 2018). Besides, Chinese-style fiscal decentralization makes the central government largely determine local official promotions (Bowman Cutter and DeShazo, 2007), resulting that local officials concern more about economic development and tend to expand investments in industries with a high return on GDP (Shen et al., 2020). Moreover, compared to environmental protection, economic development can generate more tax revenue for local governments, thereby alleviating fiscal pressure to some extent (Bai et al., 2019). Thus, we put forward Hypothesis 2.

Hypothesis 2: Local fiscal pressure restricts the effectiveness of ETS.

Hypothesis 2.1: Local fiscal pressure harms the abatement effect of ETS.

According to Eqs 6, 7, the profitability differential between the inclusion and exclusion of ETS is contingent upon the trading price p_{trade}, the decontamination amount of enterprises e_d, the emission quota e_0, and the excess emissions fine F. As illustrated above, e_0 is affected by local fiscal pressure. In addition, F is determined by local governments. When local governments face serious fiscal pressure, penalty incomes become an important non-tax income of local governments and keep rising (Jia et al., 2011; Zhao and Jia, 2016).

Eqs 6, 7 are reflected in Figure 2 to visually show the change in profits relative to emission reduction. The blue line depicts the variations in profitability differential for low-emitting enterprises corresponding to their emission reduction. The solid red lines represent the profit changes of high-emitting enterprises under the circumstance of $p_{trade} - F > 0$. As the penalty F increases, both the slope and intercept of the line of H enterprises become smaller, that is, the line moves downward and becomes flat. When F exceeds p_{trade}, the slope and intercept of the line become negative, which is represented by a red dashed line.

The intercepts of the lines in Figure 2 can reflect the impact of local fiscal pressures on the economic effects of ETS. For both H and L enterprises, the intercepts of the lines all include a portion of the initial quota e_0 that would be affected by financial pressures as stated above. Therefore, it is demonstrated that fiscal pressure has an impact on enterprises' profit changes brought by ETS. Based on the aforementioned analysis, this impact is negative, thus Hypothesis 2.2 is posited below.

Hypothesis 2.2: Local fiscal pressure has a negative impact on the economic effect of ETS.

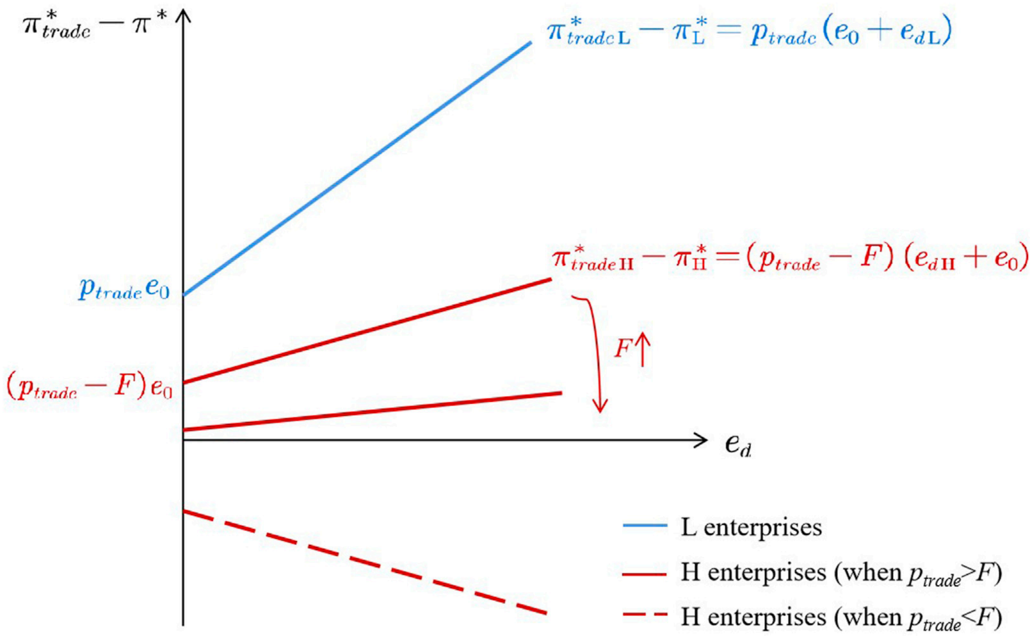

FIGURE 2
Profit change analysis.

The slopes of the lines in Figure 2 can tell us how local fiscal pressure affects the transmission from emission reduction to profit promotion. For H enterprises, the slope includes a portion coming from the penalty F which is determined by local governments. As illustrated above, local governments facing serious fiscal pressure may increase penalty incomes. When F increases to the point where the slope is negative, more emission reduction (e_d) leads to fewer profits ($\pi^*_{tradeH} - \pi^*_H$). It can be seen that the slope reflects the transmission efficiency from emission reduction to profit promotion. Since the slope is affected by fiscal pressure, we propose Hypothesis 2.3.

Hypothesis 2.3: Local fiscal pressure impairs the transmission from emission reduction to profit promotion.

4 Materials and methods

4.1 Econometric model specification

Eliminating the impact of unobservable confounders is one of the greatest challenges to correctly diagnosing a policy effect. DID can infer causality using observational data and mitigate the endogeneity problem. Thus, we adopt the DID strategy, treating the ETS pilot policy as a quasi-experiment and separating the samples into the treated group and the controlled group.

The method framework is as follows: the classical DID model is adopted to evaluate the abatement effect and the economic effect of the policy; the mediating effect model is employed to test the transmission role of emission reduction; the triple-difference framework and subsample regressions are used to investigate the impact of local fiscal pressure and the regional heterogeneity of policy effects.

4.1.1 DID model

$$\ln SO_{2it} = \alpha_0 + \alpha_1 Treat_i \times Post_t + \gamma' Control_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (10)$$

$$\ln Profits_{it} = \beta_0 + \beta_1 Treat_i \times Post_t + \delta' Control_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (11)$$

where subscripts i and t stand for the city and the year, respectively; $\ln SO_{2it}$ and $\ln Profits_{it}$ are the explained variables reflecting the environmental and economic outcomes, respectively. $Treat_i$ is a group dummy variable and is equal to 1 if a city i belongs to the treatment group, and 0 otherwise; $Post_t$ is a time dummy variable with a value of 1 when the year t is after policy implementation, and 0 otherwise. α_1 and β_1 denote the coefficients on the interaction terms in Eqs 10, 11, reflecting the policy impact on changes in emissions and profits, respectively. $Control_{it}$ denotes a vector of control variables. μ_i is the city-fixed effect and λ_t is the year-fixed effect, controlled to eliminate impacts of sample and time variation; ε_{it} is the error term.

To accurately identify the causal effect in the DID framework, the parallel trend hypothesis must be satisfied. Referencing prior research (Greenstone and Hanna, 2014; Xuan et al., 2020; Liu et al., 2021), we conduct Eq. 12 which can not only test the parallel trend but also make a dynamic analysis of the policy effect.

$$Y_{it} = \alpha_0 + \sum_{2004}^{T} \alpha_t Treat_i \times Year_t + \varphi' Control_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (12)$$

where Y_{it} denotes the explained variables ($\ln SO_{2it}$ and $\ln Profits_{it}$). $Year_t$ is a year dummy variable with t ranging from 2004 to 2017, considering that the number of dummy variables should be one less than the number of categories.

4.1.2 Mediating effect model

The mediating effect model (Baron and Kenny, 1986) is applied to investigate the transmission role of emission reduction between ETS implementation and economic returns. First, Eq. 11 is employed to identify the total effect (β_1). Second, Eq. 10 is used to examine the impact of the explanatory variable on mediating variable (α_1). Third, Eq. 13 is conducted to identify the direct effects (η_1). If both coefficients α_1 and η_2 are significant, $\alpha_1 \times \eta_2$ reflects the indirect (mediating) effect of the policy.

$$\ln Profits_{it} = \eta_0 + \eta_1 Treat_i \times Post_t + \eta_2 \ln SO_{2it} + \omega' Control_{it} + \mu_i + \lambda_t + \varepsilon_{it} \tag{13}$$

4.1.3 Triple-difference model

To determine whether the fiscal pressure ($Fiscal\_pressure$) of local governments has an impact on the effectiveness of ETS, we employ a triple-difference framework, precisely as Eq. 14. Compared to grouped regressions, this model can avoid the identification interference caused by differences in the coefficients of control variables between groups.

$$\begin{aligned} Y_{it} = {} & \alpha_0 + \alpha_1 Treat_i \times Post_t \times Fiscal\_pressure_{it} \\ & + \alpha_2 Treat_i \times Post_t + \alpha_3 Treat_i \times Fiscal\_pressure_{it} \\ & + \alpha_4 Post_t \times Fiscal\_pressure_{it} + \alpha_5 Fiscal\_pressure_{it} \\ & + \gamma' Control_{it} + \mu_i + \lambda_t + \varepsilon_{it} \end{aligned} \tag{14}$$

To further scrutinize the disparity in policy effects among regions, the total sample is subcategorized into the eastern, central, and western regions[5]. The triple-difference specification with two region dummy variables is presented as Eq. 15. Due to three region categories, two region dummy variables ($Region1$ and $Region2$) are defined. $Region1$ is an indicator variable with the value 1 if the city i is included in the eastern region and 0 otherwise. $Region2$ indicates whether or not a city belongs to the central region. The two region dummy variables ($Region1$ and $Region2$) and two double-interaction terms ($Treat_i \times Region1$ and $Treat_i \times Region2$) are omitted since the city-fixed effect and year-fixed effect are already controlled in the equation. The coefficients on the triple-interaction terms $Treat_i \times Post_t \times Region1$ (α_2) and $Treat_i \times Post_t \times Region2$ (α_4) as well as the double-interaction term $Treat_i \times Post_t$ (α_1) merit attention. For the eastern, central, and western regions, the average treatment effect of the policy can be represented by $\alpha_1 + \alpha_2$, $\alpha_1 + \alpha_4$, and α_1, respectively.

$$\begin{aligned} Y_{it} = {} & \alpha_0 + \alpha_1 Treat_i \times Post_t + \alpha_2 Treat_i \times Post_t \times Region1 \\ & + \alpha_3 Post_t \times Region1 + \alpha_4 Treat_i \times Post_t \times Region2 \\ & + \alpha_5 Post_t \times Region2 + \gamma' Control_{it} + \mu_i + \lambda_t + \varepsilon_{it} \end{aligned} \tag{15}$$

4.2 Variables and data

4.2.1 Sample and data

The research samples consist of 284 cities from 30 provinces of inland China (excluding Taiwan, Macau, Hong Kong, and Tibet due to a lack of data). The research period is set from 2003 to 2017 for the following reasons. First, the 2014 Guiding Opinions set the target that the pilot work would be basically completed by 2017. Secondly, on 1 January 2018, China officially implemented the environmental protection tax, of which the taxable pollutants such as SO_2 and nitrogen oxides (NO_X) are duplicated with the objects of emission rights trading. Besides, missing data prevents us from extending the research period further. Specifically, the data of total fixed assets, total current assets, and total profits of industrial enterprises above the designated size (IEADS) in 2018, and the data of industrial emissions (industrial SO_2, NO_X, and soot) and energy consumption (electricity consumption for industrial) before 2003 are missing. Nevertheless, this study covers long enough periods before and after the implementation of the policy.

This study includes pilot areas approved in both 2002 and 2007 as the treatment group and regards 2007 as the external shock time of the quasi-experiment. The 2002 SO_2 ETS pilot policy[6] was mainly implemented in the electricity industry with no trading platform, and a very limited number of transactions occurred (Huang et al., 2021). However, the 2007 ETS pilot policy, constructing trading platforms and covering the industries of power, cement, steel, petrochemical, glass, etc., are considered more effective (Ren et al., 2020; Huang et al., 2021). The latter is also instructive for the pilot areas that were approved before but made no substantial progress. Besides, the omission of the pilot areas approved in 2002 may lead to bias in the results, so these areas are also taken into account as the treatment group. Eventually, the treatment group includes Shanghai, Tianjin, Chongqing, Shandong, Shanxi (a), Jiangsu, Henan, Zhejiang, Hubei, Hunan, Hebei, Shanxi (b), and Inner Mongolia autonomous (see Figure 3). 126 cities are classified into the treatment group[7].

The basic data source is the China City Statistical Yearbook (2004–2018) and statistical yearbooks of various provinces and cities, with a few missing indicators in different years or cities. In the placebo test part, PM2.5 data is derived from the Atmospheric Composition Analysis Group of Dalhousie University, and weather data is from China Surface Climatological Data Set V3.0.

4.2.2 Core variables

The dependent variables in this article are denoted by $\ln SO_{2it}$ and $\ln Profits_{it}$ to reflect the environmental and economic outcomes, respectively.

$\ln SO_{2it}$ is measured by the logarithms of industrial SO_2 emissions. In relevant research, carbon emissions or intensity (Chen et al., 2020; Feng et al., 2022), SO_2 emissions (Ren et al.,

5 According to the NDRC, the eastern region includes Beijing, Tianjin, Shanghai, Hebei, Jiangsu, Zhejiang, Shandong, Liaoning, Fujian, Guangdong, and Hainan; the central region refers to Shanxi, Henan, Hubei, Hunan, Jilin, Heilongjiang, Anhui, and Jiangxi; the western region includes Inner Mongolia, Shanxi (b), Chongqing, Yunnan, Guangxi, Sichuan, Guizhou, Tibet, Gansu, Qinghai, Ningxia, and Xinjiang.

6 Shandong, Shanxi (a), Jiangsu, Henan, Tianjin, Shanghai, and Liuzhou were approved as pilot areas in the 2002 SO_2 ETS pilot policy.

7 The city of Liuzhou, approved in 2002 in Guangxi province, as an exception, was not included in the treatment group because of missing data, which is reasonable considering that the Guangxi province was not the pilot area and Liuzhou is neither a capital city nor a municipality.

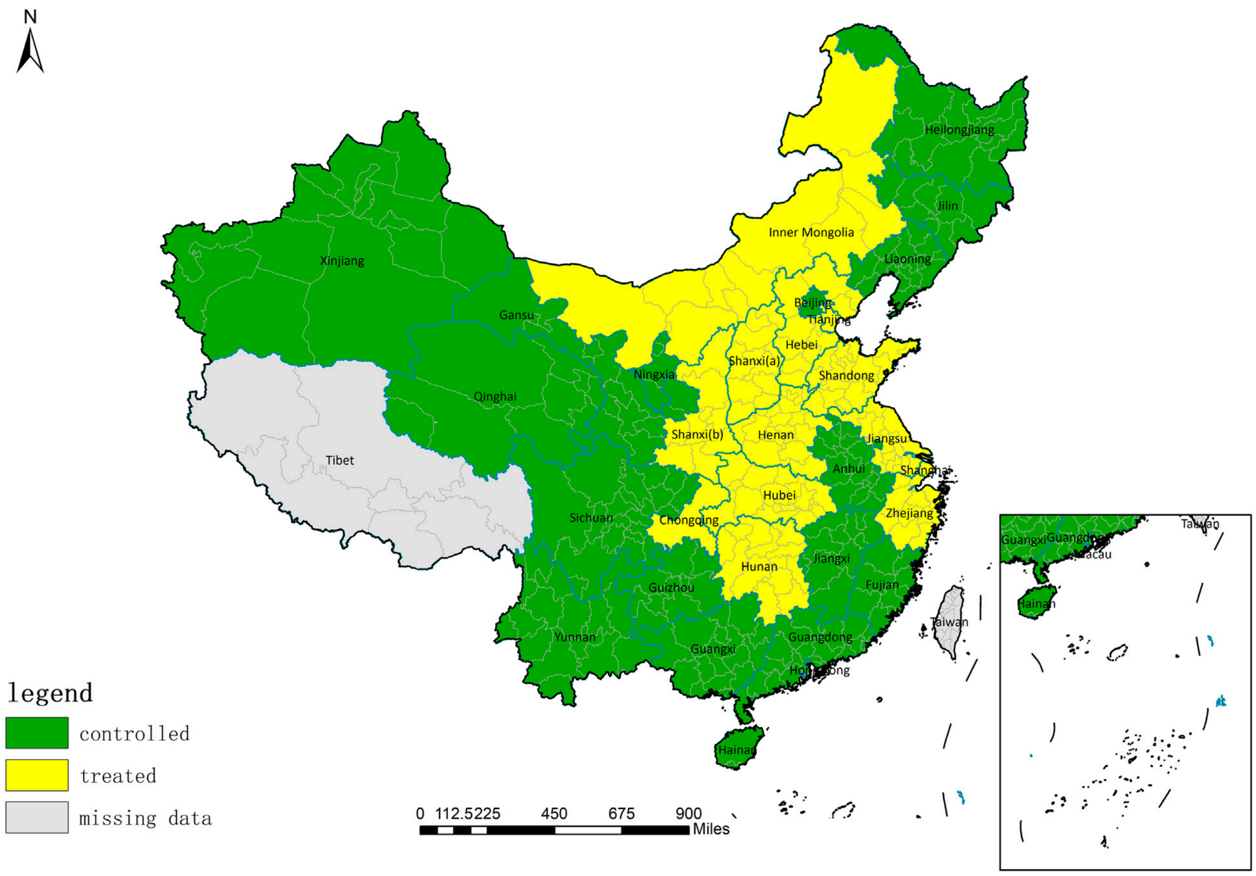

FIGURE 3
The geographical distribution of the ETS pilots in China. Data source: 1:1,000,000 national basic geographic database of the National Catalogue Service for Geographic Information.

2020; Huang et al., 2021), and PM2.5 (Yan et al., 2020; Liu et al., 2021) are generally used to measure environmental outcomes. This paper focuses on pollutant emissions trading but not carbon emissions trading. SO_2 from industrial emissions is one of the primary objectives in pollutant emissions trading.

$\ln Profits_{it}$ is measured by the logarithms of the total profits of IEADS. Scholars usually apply the gross domestic product (GDP) and *per capita* GDP (Hou et al., 2020), industrial output (Huang et al., 2021), and employment (Ren et al., 2020) to represent economic performance. However, ETS can influence the emission costs of industrial enterprises through the price mechanism and consequently impact profits. Consequently, we measure economic outcomes using industrial profits, which encompass both output and cost concepts.

The core explanatory variables are the policy variable ($Treat_i \times Post_t$) and the fiscal pressure of local governments ($Fiscal\_pressure$). $Treat_i \times Post_t$ is described in Section 4.1.1. $Fiscal\_pressure$, according to previous articles (Bai et al., 2019; Shen et al., 2020), is measured by the ratio of the difference between general public budget expenditures and revenues to GDP.

4.2.3 Control variables

Control variables for estimating environmental effects are selected based on the IPAT model (Ehrlich and Holdren, 1971), which indicates that population (P), affluence (A), and technology (T) are the primary impacts (I) on the environment. Therefore, population (*Population*), *per capita* gross regional product (*pGDP*), and technology innovation (*Tech_innovation*) are included. In addition, industrial structure (*Ind_structure*) is added, considering that the economic structure is also the primary factor. Besides, foreign direct investment (*FDI*) has a diffusion effect on improving technology and environmental management experience (Wang et al., 2021).

Control variables for estimating economic effects are considered from the following aspects: First, to make profits, fixed assets (*Fixed_assets*) such as houses, factories, and large machinery and equipment are necessary capital inputs. Net current assets (*Current_assets*) reflect the liquidity constraints that could severely limit production input (Wang et al., 2019). Second, labor forces can influence both production output and factor cost in quantity and quality. Therefore, the number of employees in the secondary industry (*Ind2_labor*) and the structure of employees (*Emp_structure*) are included to represent the quantity of the labor force, and the local general public budget expenditure on education (*Edu_expenditure*) is added to represent the quality of the labor force. Third, technology innovation (*Tech_innovation*) and local general public budget expenditure on science and technology (*Sci_expenditure*) are selected for controlling the level

TABLE 1 The definitions of the variables in the study.

Variables	Definition	Unit
lnProfits	Total profits of IEADS (take the logarithmic value)	10 billion yuan
$lnSO_2$	The volume of industrial SO_2 emission (take the logarithmic value)	Ton
Fiscal_pressure	The ratio of the difference between general public budget expenditures and revenues to GDP	
lnPopulation	Household registered population at year-end (take the logarithmic value)	10 thousand persons
lnpGDP	Per capita gross regional product (GRP) (take the logarithmic value)	Yuan
Ind_structure	The ratio of GRP of secondary industry to GRP of tertiary industry	
FDI	Actual foreign investment	10 million yuan
lnTech_innovation	Total number of patent authorizations (take the logarithmic value)	Piece
lnFixed_assets	The annual average balance of net fixed assets of IEADS (total fixed assets) (take the logarithmic value)	10 million yuan
Current_assets	The annual average balance of net current assets of IEADS (total current assets) (take the logarithmic value)	10 million yuan
lnInd2_labor	The number of employees in the secondary industry (take the logarithmic value)	Person
lnEdu_expenditure	Expenditure for education in local general public budget expenditure (LGPBE) (take the logarithmic value)	10 million yuan
lnSci_expenditure	Expenditure for science and technology in LGPBE (take the logarithmic value)	10 million yuan
Emp_structure	Persons employed in private enterprises and self-employed individuals in urban areas/Persons employed in urban units at year-end	
lnEnergy	Electricity consumption for industrial (take the logarithmic value)	10 million kwh

of technological development and the degree of emphasis. Besides, energy consumption (*Energy*) is added for the reason that industrial output is sensitive to it (Huang et al., 2021); industrial structure (*Ind_structure*) and foreign investment (*FDI*) are controlled due to their impacts on the flows of capital and labor.

The definitions of relevant variables are depicted in Table 1.

5 Results and discussion

5.1 The dual environmental and economic effects of ETS

The baseline regression results of the policy effects on emissions reduction and profit growth are shown in Table 2. Columns (1) and (3) depict the estimated results with only the city-fixed effect and the year-fixed effect controlled, eliminating the impacts of individual heterogeneity and time variation. Columns (2) and (4) add all the control variables in Eqs 10, 11, which control for the city-fixed effect and year-fixed effect. The coefficients on the interaction term $Treat_i \times Post_t$ are of interest, as they capture the policy effects on curbing industrial emissions and progressing profits. In columns (1) and (2), the interaction term coefficients $Treat_i \times Post_t$ are negative, indicating that industrial SO_2 emissions in pilot areas decreased after the implementation of ETS. Meanwhile, columns (3) and (4) display positive coefficients on the interaction term $Treat_i \times Post_t$, implying that the policy elevated industrial profits in regulated areas. Industrial enterprises are incentivized by the ETS to improve their green production processes and reduce emissions, thereby cutting compliance costs such as purchasing excess emission allowances or paying penalties. Emission reductions propelled by technological advancements enhance productivity while upholding a constant level of emissions. The combination of reduced compliance costs and increased output culminates in amplified industrial gains.

According to the parallel trend hypothesis, the interaction term coefficients before policy implementation should be insignificant, which is supported in Table 3 and Figure 4. Dynamic analysis reveals varying degrees of hysteresis impact on curbing SO_2 emissions and promoting profit growth. In 2011, there was a rebound in the abatement effect of the policy. One possible explanation is that to recover and develop the economy after the 2008 financial crisis, China actively took measures to support the development of production in 2009. Under the fiscal decentralization system, local governments affected by economic performance assessment standards may sacrifice the environment to pursue economic development, which results in a rise in industrial emissions. The policy effect on industrial profits did not reach statistical significance until 2009 and maintained a relatively stable positive impact since then, denoting a hysteretic but positively cumulative dynamic effect on bolstering industrial profit growth. The impact of ETS on reducing emissions depends on the enforcement of local governments within a total emissions control framework, while its economic benefits stem from emitters' gradual adjustments driven by profit maximization. As a result, economic effects generally have a longer latency than environmental effects before the policy takes effect (Sueyoshi and Yuan, 2017).

Table 4 shows the results of robustness tests: (1) The staggered DID is conducted to address the problem that the execution time of ETS varies across pilot areas (shown in the first two columns of Panel A). We searched the websites of the Ecology and Environment Departments (Bureaus) of each province (municipality) for ETS-related information and obtained the execution time in each pilot area. If the policy was executed before 2007 (only in Shandong and Jiangsu), we unanimously set 2007 as the start date of the policy. Considering that staggered DID may lead to biased estimates, we

TABLE 2 The baseline regression results of the effects of ETS.

	lnSO2		lnProfits	
	(1)	(2)	(3)	(4)
$Treat_i \times Post_t$	−0.265***	−0.248***	1.141***	0.891***
	(0.036)	(0.036)	(0.109)	(0.097)
lnPopulation		−0.050		
		(0.046)		
lnpGDP		0.187***		
		(0.042)		
Ind_structure		−0.006		0.048
		(0.022)		(0.098)
FDI		−0.0004***		0.004***
		(0.0001)		(0.001)
lnTech_innovation		0.005		−0.157**
		(0.022)		(0.052)
lnFixed_assets				−0.021
				(0.08)
lnCurrent_assets				0.193
				(0.1)
lnInd2_labor				0.414***
				(0.083)
lnEdu_expenditure				0.39***
				(0.061)
lnSci_expenditure				−0.167
				(0.105)
Emp_structure				−0.107*
				(0.045)
lnEnergy				0.021
				(0.047)
Constant	10.563***	8.917***	1.194***	−4.463***
	(0.013)	(0.506)	(0.04)	(1.962)
City FE	Y	Y	Y	Y
Year FE	Y	Y	Y	Y
N	4,230	4,196	4,234	4,092
Adj. R^2	0.797	0.801	0.711	0.749

Note: Standard errors in parentheses, $^*p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

TABLE 3 Parallel trend test and dynamic analysis.

Year	$lnSO_2$	lnProfits
	(1)	(2)
2004	0.086	0.068
	(0.094)	(0.237)
2005	0.028	0.082
	(0.091)	(0.225)
2006	−0.037	0.178
	(0.081)	(0.214)
2007	−0.143	0.256
	(0.079)	(0.197)
2008	−0.192*	0.257
	(0.077)	(0.221)
2009	−0.252***	0.442*
	(0.076)	(0.181)
2010	−0.252**	0.656**
	(0.079)	(0.217)
2011	0.050	1.085***
	(0.100)	(0.255)
2012	−0.191*	1.231***
	(0.086)	(0.238)
2013	−0.239	1.197***
	(0.127)	(0.202)
2014	−0.174*	1.429***
	(0.085)	(0.227)
2015	−0.232**	1.714***
	(0.080)	(0.427)
2016	−0.367***	1.398***
	(0.095)	(0.260)
Constant	8.862***	−4.382***
	(0.510)	(1.175)
Controls	Y	Y
City FE	Y	Y
Year FE	Y	Y
N	4,196	4,092
Adj. R^2	0.802	0.753

Note: Standard errors in parentheses, $^*p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

just apply it to robustness tests (for details see Supplementary Information S1; Supplementary Tables S1; Supplementary Figures S1 in Supplementary Material). (2) We make variable substitutions to support robustness. Specifically, industrial SO_2 emissions are replaced with the emissions of industrial NO_X ($lnNO_X$) and soot (ln*Soot*), and industrial profits are substituted with the value-added tax (*VAT*) payable by IEADS (shown in the last three columns of Panel A). (3) The propensity score matching (PSM) approach is adopted to alleviate the problem of self-selection. ETS pilot areas are typically selected based on the regional economic development level, pollution level, and industrial structure (Han et al., 2019; Huang

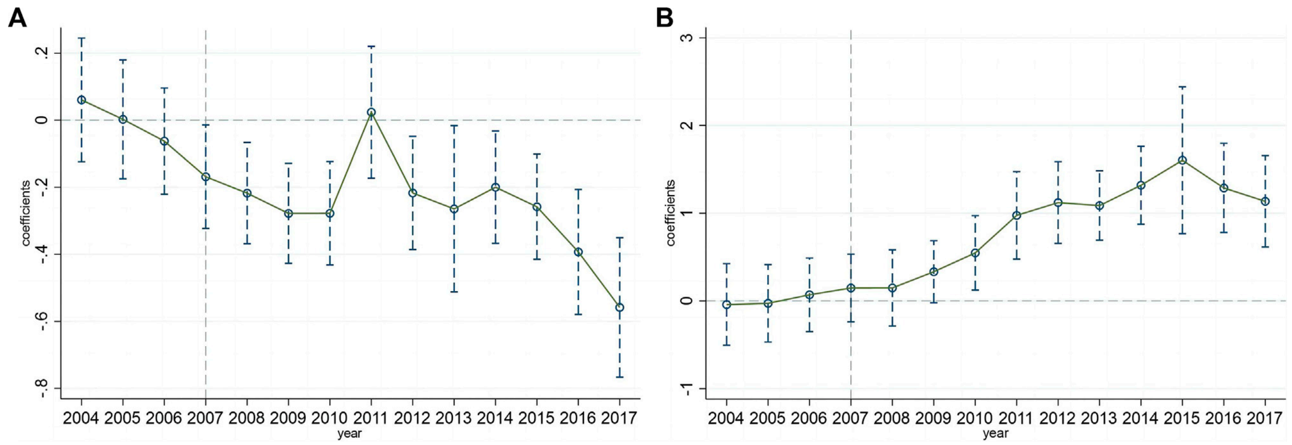

FIGURE 4
The plots of the parallel trend test. [**(A)** $\ln SO_2$; **(B)** lnProfits].

et al., 2021). However, PSM is appropriate for cross-sectional data, whereas the DID framework necessitates panel data. Most existing studies address this issue by treating the panel data as cross-sectional data and matching directly, which leads to another concern of time mismatch. Performing a phase-by-phase matching on each cross-section of panel data can solve the problem of time mismatch (Böckerman and Ilmakunnas, 2009), but the control group is unstable. Due to the reasons above, we just take PSM-DID as robustness tests and conduct both cross-sectional and phase-by-phase matching (shown in Panel B, for details see (Supplementary Tables S2–S6; Supplementary Figures S2–S4 in Supplementary Material). (4) We alter econometric model specifications, controlling $Treat_i$ and $Post_t$ instead of the city-fixed effect and year-fixed effect (shown in Panel C).

Besides, two placebo tests are conducted as follows: (1) To avoid the impact of parallel policies, such as the Action Plan of Air Pollution Prevention and Control and the Carbon ETS, we substitute industrial SO_2 emissions with PM2.5. On the one hand, the primary target of Carbon ETS is the greenhouse gases (GHG) that have the same sources and a coexistence effect with PM2.5 (Driscoll et al., 2015; Liu et al., 2021). If PM2.5 does not decrease during our research period, we can assume that the parallel policies have little disturbance on the policy effect. On the other hand, according to the dynamic analysis in Table 3, the 2007 ETS policy had already come into effect before the proposal of the two parallel policies[8]. Panel D of Table 4 presents the results on PM2.5. Considering that PM2.5 is easily influenced by weather, green space coverage, and the level of urban transportation infrastructure, these variables (denoted by WGT[9]) are controlled for (2) To avoid other random factors and obtain a credible causal effect, we randomly choose 126 cities as the pseudo-treatment group, repeating 500 times (see Figure 5). The estimated result for the pseudo-treatment group demonstrates that the average coefficients of the policy effects on $\ln SO_2$ and $\ln Profits$ are highly close to zero, with the average p-values being nonsignificant in statistics (see Supplementary Table S7 in Supplementary Material). The majority of dots in Figure do not reach the significant level of 0.05 (represented by the horizontal red dotted lines) and are considerably far from the coefficients for the real treatment group (represented by the vertical red dotted lines), implying that policy has almost no impact on the pseudo-treatment group.

5.2 The internal relationship between the environmental and economic effects of ETS

The preceding part provides empirical evidence that the implementation of ETS in China is generally conducive to emission reduction and profit promotion. In this part, we explore the inner relationship between the environmental effect and the economic effect to reveal the intrinsic mechanism for achieving dual dividends. Table 5 presents the results of mediating effect test. Columns (1) and (2) reiterate the results from columns (2) and (4) of Table 2 and column (3) shows the regression result of Eq. 13 As depicted in the first three columns, the total effect ($\beta_1 = 0.891$) and direct effect ($\eta_1 = 0.852$) on $\ln Profits$ as well as the coefficients of α_1 ($\alpha_1 = -0.248$) and η_2 ($\eta_2 = -0.142$) are all significant, showing a partial mediating effect. The result implies that emission reduction is one transmission channel to achieve economic benefits, which is consistent with our theoretical analysis. Hypothesis 1 stands. Under the circumstances of ETS, enterprises are inclined to promote their green production processes and reduce emissions to avoid the expenditure on purchasing excess emission rights or paying fines. Instead, they can reap economic benefits by selling or storing surplus emission rights (Ji et al., 2017; Narassimhan et al., 2018). Once an enterprise reaches a certain level of technological advancement (where the

8 The Action Plan was released in 2013. The Carbon ETS was proposed in 2011 and initiated in 2013.

9 Weather includes wind speed, rainfall, humidity, sunshine and temperature, based on data from China Surface Climatological Data Set V3.0. Green space *per capita* is calculated by the area of parks green land divided by the household registered population at year-end, and the level of urban transportation infrastructure is calculated by the number of buses per 10 thousand people, with relevant data obtained from the China City Statistical Yearbook.

TABLE 4 Robustness test.

Panel A: Staggered DID and variable substitutions					
	Staggered DID		Variable substitutions		
	$\ln SO_2$	lnProfits	$\ln NO_X$	lnSoot	VAT
Treat × $Post_{(it)}$	−0.172***	0.678***	−0.228***	−0.248***	0.326***
	(0.028)	(0.104)	(0.042)	(0.042)	(0.033)
Constant	8.843***	−4.418***	9.411***	9.540***	−0.704
	(0.511)	(1.185)	(0.584)	(0.581)	(0.493)
Controls	Y	Y	Y	Y	Y
City FE	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y
N	4,196	4,092	4,182	4,196	4,042
Adj. R^2	0.7998	0.748	0.718	0.720	0.819

Panel B: PSM-DID						
	PSM-DID		Staggered DID with PSM			
	(Weight not empty)		Cross-section matching		Phase-by-phase matching	
	$\ln SO_2$	lnProfits	$\ln SO_2$	lnProfits	$\ln SO_2$	lnProfits
Treat × Post	−0.243***	0.593***	−0.164***	0.487***	−0.113***	0.333***
	(0.039)	(0.094)	(0.029)	(0.101)	(0.029)	(0.114)
Constant	8.871***	−5.145***	8.768***	−5.195***	9.403***	−5.707***
	(0.547)	(2.109)	(0.545)	(1.310)	(0.525)	(1.700)
Controls	Y	Y	Y	Y	Y	Y
City FE	Y	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y	Y
N	3,720	3,516	3,720	3,516	3,158	3,087
Adj. R^2	0.776	0.788	0.775	0.788	0.799	0.736

Panel C: Altering model specifications			Panel D: Placebo test of changing $\ln SO_2$ to PM2.5		
	$\ln SO_2$	lnProfits		PM2.5	PM2.5
Treat × Post	−0.206**	0.808***	Treat × $Post_{(it)}$	0.038***	0.016
	(0.072)	(0.093)		(0.010)	(0.010)
Constant	3.132***	−4.506***	Constant	4.339***	7.235***
	(0.436)	(0.446)		(0.142)	(0.6996)
Controls	Y	Y	WGT	N	Y
Treat FE	Y	Y	Controls	Y	Y
Post FE	Y	Y	City FE	Y	Y
N	4,196	4,092	Year FE	Y	Y
Adj. R^2	0.215	0.604	*N*	4223	4181

Note: Standard errors in parentheses, $^*p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

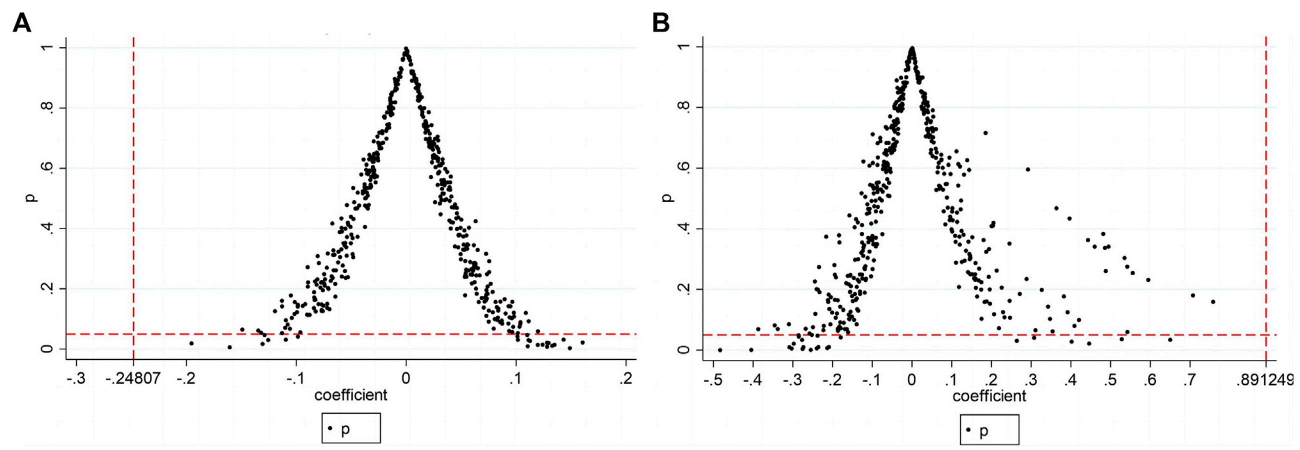

FIGURE 5
Constructing pseudo-treatment groups. [**(A)** $\ln SO_2$; **(B)** lnProfits].

TABLE 5 The test of mediating effect.

	$\ln SO_2$	lnProfits		F.lnProfits	
	(1)	(2)	(3)	(4)	(5)
Treat × Post	−0.248***	0.891***	0.852***	0.897***	0.859***
	(0.036)	(0.097)	(0.098)	(0.100)	(0.100)
$\ln SO_2$			−0.142***		−0.163***
			(0.040)		(0.042)
Constant	8.917***	−4.463***	−3.422**	−2.380	−1.254
	(0.506)	(1.962)	(1.228)	(1.725)	(1.716)
Controls	Y	Y	Y	Y	Y
City FE	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y
N	4,196	4,092	4,067	3,821	3,808
Adj. R^2	0.801	0.749	0.749	0.753	0.752
Indirect effect (Sobel test)		0.035**	(0.013)	0.036**	(0.013)
Proportion of indirect effect	Sobel	0.0402		0.0409	
	Bootstrap	0.0402		0.0409	

Note: Standard errors in parentheses, *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

unit variable decontamination cost falls below the emission trading price, as expounded in Section 3.2.1), the economic benefits derived from reducing emissions can offset or even surpass any additional regulatory costs incurred.

To ensure robustness, we conduct the mediating effect test based on staggered DID (see Panel A of Table 6). Additionally, to avoid the interference of different sets of control variables in the regressions of $\ln SO_2$ and $\ln Profits$, we conduct the Sobel test and Bootstrap test in which all control variables are added. The main results are shown in the last three lines of Tables 5, 6 (Panel A), presenting the mediating effect of $\ln SO_2$ counts for 4.02%–4.13% of the total effects. The Bootstrap test, which can overcome the normal distribution assumption of the Sobel test, reports the same result after 500 iterations. All the tests reveal a consistent result that the change in SO_2 emissions plays a partial mediating role between the implementation of the policy and industrial profit growth, implying that ETS can progress economic development by curbing emissions (for details see Supplementary Tables S8–S11 in Supplementary Material).

TABLE 6 Robustness test of mediating effect.

Panel A: Mediating effect test based on staggered DID			
	$lnSO_2$	lnProfits	
	(1)	(2)	(3)
Treat × $Post_{it}$	−0.172***	0.678***	0.645***
	(0.028)	(0.104)	(0.105)
$lnSO_2$			−0.152***
			(0.040)
Constant	8.843***	−4.418***	−3.307**
	(0.511)	(1.185)	(1.231)
Controls	Y	Y	Y
City FE	Y	Y	Y
Year FE	Y	Y	Y
N	4,196	4,092	4,067
Adj. R^2	0.7998	0.748	0.748
Indirect effect (Sobel test)	0.028**		(0.010)
	Sobel	0.0413	
Proportion of indirect effect	Bootstrap	0.0413	

Panel B: IV regressions					
	OLS	TSLS	LIML	GMM	IGMM
$lnSO_2$	−0.183***	−7.869***	−7.970***	−8.024***	−8.029***
	(0.040)	(1.837)	(1.877)	(1.832)	(1.833)
Constant	−3.606***	57.691***	58.469***	59.001***	59.043***
	(1.252)	(14.788)	(15.094)	(14.726)	(14.732)
City FE	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y
N	4,067	3,821	3,821	3,821	3,821
Adj. R^2	0.7442				

Note: Standard errors in parentheses, $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

For the endogeneity, we use DID method, fixed effects, and PSM method to alleviate it to some extent. However, the endogeneity of reverse causality between emission reduction and profit growth may still exist. Rising profits provide industrial enterprises with economic strength to cut emissions. We adopt two strategies: First, considering that future profits can hardly change the emissions generated previously, we use the next period of industrial profits instead of the current period one as the explained variable, and the results are shown in columns (4) and (5) of Table 5. Second, we take the domestic garbage disposal rate and green space *per capita* as IVs to mitigate the endogeneity of the reverse causality. Because the selected IVs can reflect a city's attention and commitment to environmental management but are almost unable to affect the profits of industrial enterprises. Panel B of Table 6 demonstrates that the results of various estimation methods of IV regressions are consistent with ordinary least squares (OLS), to some extent, supporting the causal inference from emission reductions to profit growth. Besides two-stage least squares (TSLS), we undertake IV regressions with the limited information maximum likelihood (LIML) method, which is insensitive to weak instrumental variables, even though the selected IVs pass the weak instrument tests; taking heteroscedasticity and autocorrelation into account, we employ the generalized method of moments (GMM) and iterative GMM (IGMM). The validity test of instrumental variables and weak instrument robust tests are provided in the Supplementary Material (see Supplementary Tables S12, S13).

Overall, based on the empirical evidence of the ETS pilot policy in China, emission reduction is one transmission channel to realize economic benefits in the scenario of emissions trading, which fundamentally explains the internal

TABLE 7 The impact of fiscal pressure.

Panel A: The moderating effect of fiscal pressure						
			Fiscal pressure subsamples			
	$lnSO_2$	lnProfits	Low	High	Low	High
	(1)	(2)	(3)	(4)	(5)	(6)
Treat × Post × c_Fiscal_pressure	2.291**	−18.898***				
	(0.854)	(2.395)				
Treat × Post	−0.0001	−0.535***	−0.281***	−0.059	0.992***	0.364***
	(0.065)	(0.154)	(0.052)	(0.075)	(0.155)	(0.123)
Treat × c_Fiscal_pressure	−2.828***	18.759***				
	(0.898)	(2.496)				
Post × c_Fiscal_pressure	2.131***	−5.944***				
	(0.611)	(1.058)				
Fiscal_pressure	−1.582*	4.453***				
	(0.654)	(1.133)				
Constant	9.461***	−6.194***	11.628***	6.545***	−9.773***	−6.628***
	(0.526)	(1.186)	(0.745)	(0.869)	(2.881)	(1.068)
Controls	Y	Y	Y	Y	Y	Y
City FE	Y	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y	Y
N	4,196	4,092	2,102	2,050	2,077	1,970
Adj. R^2	0.805	0.760	0.806	0.7927	0.758	0.671
Test of coefficients difference (0–1):			−0.223***		0.628***	
Panel B: Mediating effect test based on fiscal pressure subsamples						
	High fiscal pressure subsample			Low fiscal pressure subsample		
	$lnSO_2$	lnProfits		$lnSO_2$	lnProfits	
	(1)	(2)	(3)	(4)	(5)	(6)
Treat × Post	−0.059	0.364**	0.348**	−0.281***	0.992***	0.944***
	(0.075)	(0.123)	(0.123)	(0.052)	(0.155)	(0.159)
$lnSO_2$			−0.069**			−0.181*
			(0.021)			(0.081)
Constant	6.545***	−6.628***	−6.300***	11.628***	−9.773***	−8.113**
	(0.869)	(1.068)	(1.089)	(0.745)	(2.881)	(2.966)
Controls	Y	Y	Y	Y	Y	Y
City FE	Y	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y	Y
N	2,050	1.970	1,953	2,102	2,077	2,070
Adj. R^2	0.793	0.671	0.673	0.806	0.758	0.757
Indirect effect	0.009		(0.006)	0.052*		(0.026)
Proportion of indirect effect	0.024			0.052		

Note: Standard errors in parentheses, $^*p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$. c_Fiscal_pressure denotes the centralized Fiscal_pressure.

TABLE 8 The test of regional heterogeneity.

	$\ln SO_2$			lnProfits			$\ln SO_2$	lnProfits
	Eastern	Central	Western	Eastern	Central	Western		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Treat × Post	−0.323***	−0.160***	−0.017	0.806***	0.335***	0.928**	−0.004	0.989**
	(0.075)	(0.046)	(0.083)	(0.210)	(0.098)	(0.287)	(0.082)	(0.311)
Treat × Post × Region1							−0.466***	0.124
							(0.109)	(0.378)
Post × Region1							0.192*	1.097***
							(0.085)	(0.137)
Treat × Post × Region2							−0.156	−0.704*
							(0.094)	(0.327)
Post × Region2							−0.062	0.183*
							(0.060)	(0.081)
Constant	9.640***	10.625***	3.777	−4.372	−10.233***	−6.261***	8.909***	−5.983***
	(0.969)	(0.722)	(2.883)	(2.295)	(1.183)	(1.761)	(0.524)	(1.155)
Controls	Y	Y	Y	Y	Y	Y	Y	Y
City FE	Y	Y	Y	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y	Y	Y	Y
N	1,505	1,462	1,229	1,481	1,417	1,194	4,196	4,092
Adj. R^2	0.810	0.781	0.813	0.827	0.790	0.405	0.802	0.758

Note: Standard errors in parentheses, $*p < 0.05$, $**p < 0.01$, $***p < 0.001$.

mechanism of realizing the dual benefits, emphasizing the synergistic effect instead of a trade-off between the environment and economy.

5.3 The impact of local fiscal pressure on the effectiveness of ETS

In this part, we set environmental policy analysis in the context of China's fiscal decentralization system and examine the effectiveness of the ETS pilot policy under local fiscal pressure. Panel A of Table 7 depicts the impact of fiscal pressure on policy effects. In columns (1) and (2), the coefficients of the triple-interaction terms (2.291 and −18.898) are significant with opposite signs to the original double-interaction coefficients in Table 2 (−0.248 and 0.891), indicating that local fiscal pressure poses a negative impact on the effectiveness of the policy. Columns (3)–(6) present the results of subsamples of low and high fiscal pressure separated by the median of *Fiscal_pressure*. The coefficients of policy effect are significantly different between the high and low fiscal pressure subsamples, economically (with margins of −0.223 and 0.628 for $\ln SO_2$ and $\ln Profits$, respectively) and statistically (with p-values below 0.001), indicating that the policy effects in cities with higher levels of financial pressure were weaker than those in cities with lower levels, on both emission reductions and profit promotion. Both triple-difference and subsample regressions indicate that local fiscal pressure diminishes both the abatement effect and economic effect of ETS. Specifically, Hypothesis 2.1 and Hypothesis 2.2 hold.

Additionally, we investigate whether local fiscal pressure has an impact on the transmission role of emission reduction. Panel B of Table 7 depicts the mediating effect tests based on subsamples of fiscal pressure. In columns (1)–(3), the high fiscal pressure subsample shows neither a significant abatement effect nor a mediating effect. While in columns (4)–(6), the indirect effect of the low fiscal pressure subsample accounts for a higher proportion (5.2%) than that of the entire sample (4.02%), implying that lower levels of the pressure are conducive to greater transmission from emission reduction into economic benefits. The last two lines show the main results of the Sobel test, indicating the indirect effect of the high fiscal pressure subsample is insignificant, but that of another subsample is significant (with a value of 0.052 and a p-value less than 0.05) (for details see Supplementary Tables S14 in Supplementary Material). The indirect impact varies in response to divergent fiscal pressures. Higher fiscal pressure limits the capacity of local governments to effectively manage emissions trading. When local governments are captured by capital interests, potential rent-seeking corruption may result in increasing excess emission fines

TABLE 9 Regional heterogeneity in realizing dual benefits.

	Eastern			Central			Western		
	$\ln SO_2$	lnProfits		$\ln SO_2$	lnProfits		$\ln SO_2$	lnProfits	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Treat × Post	−0.323***	0.806***	0.727***	−0.160***	0.335***	0.326***	−0.017	0.928**	0.928**
	(0.075)	(0.210)	(0.215)	(0.046)	(0.098)	(0.097)	(0.083)	(0.287)	(0.288)
$\ln SO_2$			−0.186*			−0.051			−0.153*
			(0.082)			(0.042)			(0.059)
Constant	9.640***	−4.372	−3.032	10.625***	−10.233***	−9.832***	3.777	−6.261***	−5.491**
	(0.969)	(2.295)	(2.419)	(0.722)	(1.183)	(1.186)	(2.883)	(1.761)	(1.735)
Controls	Y	Y	Y	Y	Y	Y	Y	Y	Y
City FE	Y	Y	Y	Y	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y	Y	Y	Y	Y
N	1,505	1,481	1,471	1,462	1,417	1,415	1,229	1,194	1,181
Adj. R^2	0.810	0.827	0.827	0.781	0.790	0.790	0.813	0.405	0.406
Indirect effect (Sobel test)			0.067*	(0.032)	0.010	(0.008)		0.002	(0.013)
Proportion of indirect effect			0.080		0.031			0.002	
Mean of fiscal pressure			0.058		0.121			0.172	

Note: Standard errors in parentheses, *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

and transaction costs (Fan et al., 2009), as theoretically illustrated in Section 3.2.2. Thus, local fiscal pressure impairs the transmission from emission reduction to profit promotion and Hypothesis 2.3 holds.

In brief, fiscal pressure not only directly damages policy effectiveness but also indirectly affects the transmission channel for achieving dual dividends. Hypothesis 2 holds. High fiscal pressure restricts the ability of local governments to execute ETS, such as emissions monitoring, environmental regulation, and quota allocation management, which eventually undermines the abatement effect. When there is a market failure in environmental issues, local governments with high fiscal pressure are difficult to make an appropriate intervention.

5.4 Regional heterogeneity analysis

China develops unevenly across its vast territory (Chen et al., 2020), resulting in a diverse range of regional development patterns and implementation procedures of policies. Consequently, it is necessary and meaningful to probe the regional heterogeneity of the policy effects. In Table 8, the first six columns display the results based on regional subsamples. In terms of the abatement effect revealed in columns (1)–(3), the coefficients of $Treat_i \times Post_t$ for the eastern and central regions (−0.323 and −0.16, respectively) are statistically significant, whereas the coefficient for the western region (−0.017) is small and insignificant. The results indicate that implementing ETS in the western region contributed little to emission reduction. Regarding economic effects shown in columns (4)–(6), the coefficients of $Treat_i \times Post_t$ are statistically significant in the three regional subsamples, although the central region demonstrates a comparatively lower economic effect (0.335) than the eastern and western regions (0.806 and 0.928). Columns (7) and (8) illustrate the results of regional heterogeneity using the triple-difference model. The coefficients of $Treat_i \times Post_t$, which represent the policy effects in the western region, indicate no significant impact on emission reduction but a significant positive effect on industrial profit growth. The combination of coefficients of $Treat_i \times Post_t \times Region1$ and $Treat_i \times Post_t$ reflects that the implementation of ETS in the eastern region effectively reduced emissions and boosted profits. The coefficients of $Treat_i \times Post_t \times Region2$ and $Treat_i \times Post_t$ jointly suggest a significant positive economic effect but a negligible abatement effect in the central region.

To analyze the dynamic effects of the policy in different regions, we employ Eq. 12 for regional subsamples (see Supplementary Table S15 in Supplementary Material). The abatement effect first appeared in the eastern region in 2007, one year later in the central region. Since 2011, the policy effects on promoting profit growth have appeared in the eastern and central regions. Generally, the economic effect emerged later than the environmental effect, which is consistent with our preceding result at the national level. There is no meaningful evidence of policy effects in the western region. To sum up, the implementation effects of the ETS pilot policy vary among regions in China. The eastern region has achieved the dual benefits of environmental protection and economic development, whereas the central and western regions have not shown "efficient markets."

We want to further explain why the policy effect varies among regions. According to our previous analyses, it can be explained by different levels of fiscal constraint and diverse transmission efficiency from emission reduction to economic benefits. The mediating test based on regional subsamples is presented in Table 9. The indirect effect is only significant in the eastern region, which accounts for 8% of the total effect, higher than the percentage of the national level. Bootstrap test still stands in the eastern subsample (see Supplementary Table S17 in Supplementary Material). Besides, we compare the average levels of fiscal pressure in the three regions (at the last line of Table 9, details in Supplementary Tables S16). The order of fiscal pressure among regions, from lowest to highest, follows the sequence of east, central and western regions, which is consistent with the decline sequence in the abatement effect. Therefore, we perceive that the dual benefits have not been realized in the central and western regions due to not only lower abatement effects but also lower transmission efficiency from emission reduction to profit growth. Moreover, higher levels of fiscal pressure in the two regions restrict the effectiveness of the policy. On the one hand, compared to the eastern region, the ETS markets in the western and central regions are relatively underdeveloped with an incomplete trading mechanism. On the other hand, local governments facing increasingly severe fiscal pressures have limited capital expenditures on emission trading management, potentially leading to the prioritization of economic development and even rent-seeking corruption over efforts towards environmental preservation. As a result of the combination of the two aspects above, not only does ETS have a limited effect on regional emission reduction, but also the transmission mechanism from emission reduction to profit realization fails to function, thereby impeding the attainment of dual benefits.

5.5 Discussion

Based on the results of this paper, our research objectives can be addressed. First, this article provides empirical evidence that China's ETS pilot policy is conducive to emission reduction and profit promotion at a national average level, which is consistent with relevant research (Ren et al., 2020; Huang et al., 2021). The result confirms that the implementation of ETS in China performs an "efficient market" in both environmental protection and economic development. An additional finding is that the economic effect appeared later than the abatement effect because the former requires a gradual adjustment process.

Second, we explore the internal relationship between the economic and environmental effects of ETS to elucidate how the dual benefits are realized, filling an existing research gap. The result indicates that emission reduction serves as a transmission channel for achieving economic benefits, which is in line with our theoretical analysis. Our findings fundamentally explicate the internal mechanism of realizing the dual benefits, emphasizing the synergistic effect instead of a trade-off between them. Yu et al. (2022) provided micro-empirical evidence that China's A-share listed firms improved their return on assets by cutting emissions after the implementation of ETS. Distinguished from their studies, we theoretically deduce the transmission from emission reduction to economic return and test the mechanism at the city level. Examining policy effects at the city level aligns with our focus on assessing local fiscal pressures in this study.

Third, since environmental problems may encounter market failure, we take "promising governments" into consideration for assessing the effect of ETS for the first time. We find local fiscal pressure not only directly undermines policy effectiveness but also indirectly hinders the transmission channel for achieving dual dividends. Higher levels of fiscal pressure constrain the capacity of local governments to effectively manage emissions trading, compelling local governments to make a trade-off between economic development and environmental protection. Compared to environmental governance, economic development can generate more tax revenue, thereby alleviating the fiscal pressure on local governments to some extent (Bai et al., 2019). Besides, local governments facing high fiscal pressure may struggle to intervene effectively in cases of market failure, ultimately leading to an unsatisfactory implementation of environmental policies.

Although previous studies have examined the heterogeneity effects of the policy from perspectives of environmental enforcement (Ren et al., 2020) and city characteristics such as industrialization and administrative level (Huang et al., 2021), further empirical evidence and explanation are required to elucidate the divergent environmental and economic impacts of ETS across different regions. Our findings indicate that the implementation of ETS in eastern China has achieved the dual benefits of emission reduction and profit growth. However, there is insufficient evidence to support this claim for the central and western regions. Additionally, we elucidate the regional heterogeneity by the fiscal pressure constraint and the shift from emission reduction to economic benefits. The implementation of ETS in the central and western regions does not exhibit an "efficient market" of synergistic effects between the environment and economy. Meanwhile, the high fiscal pressure in these two regions may prompt local governments to abandon "racing to the top" for a "racing to the bottom" in environmental governance.

6 Conclusion and policy implications

6.1 Conclusion

China is transitioning its environmental governance patterns and increasingly prioritizing the market-based ETS. In contrast to developed economies, China's implementation of ETS occurs within a fundamentally different political-economic-institutional context. Fiscal decentralization grants local governments with authority but also amplifies their fiscal pressures. The evaluation of ETS policy in China should be situated within the institutional context of fiscal decentralization.

From a novel perspective, we integrate market-based ETS with the institutional background of fiscal decentralization to investigate the internal mechanisms and external constraints of ETS in achieving dual environmental-economic benefits under local fiscal pressure. We demonstrate that the transmission mechanism from emission reduction to economic return inherently promotes the realization of dual benefits, and propose a restrictive effect of local fiscal pressure on the effectiveness of ETS. The theoretical logic in this study can be applied to a wide range of market-based mechanisms for trading green factors, including carbon emissions, energy use rights, and natural resources. Our study provides valuable insights for China to effectively coordinate "efficient markets" and "promising governments" in environmental governance, while also serving as a reference point for other countries with similar backgrounds.

The empirical results yield three primary conclusions. First, the implementation of ETS in China generally shows an "efficient market" for both environmental protection and economic development with emission reduction serving as a transmission channel to achieve economic benefits. As more emission reductions are translated into economic gains, greater dual benefits are realized, fundamentally elucidating the internal mechanism behind achieving such dual benefits. Second, high fiscal pressure on local governments not only directly impairs policy effectiveness but also indirectly hinders the transmission channel for achieving dual dividends, which highlights the importance of "promising governments" in market-based environmental governance. Finally, the implementation of ETS has brought dual benefits to eastern China but not to the central and western regions, which can be explained from the perspectives of various levels of local fiscal pressure and differing transmission efficiencies in converting emission reductions into economic benefits.

6.2 Policy implications

To fully coordinate "efficient markets" and "promising governments" in environmental governance and improve the effectiveness of ETS, this paper proposes the following policy implications:

(1) The policy of ETS pilots is an essential exploration of environmental governance in China, having made certain achievements but still requiring great improvement. Local governments are responsible for implementing national strategies, exploring local experiences, and guiding grassroots practices. They should adhere to the combination of national top-level design and local exploration. It is urgent to accelerate the establishment of a diversified system for assessing political performance and guide local governments to attach importance to the supply of environmental public goods.
(2) The predicament of high fiscal pressure on local governments, especially the institutional fiscal pressure under fiscal decentralization, needs to be addressed. On the one hand, the fiscal powers and expenditure responsibilities of governments at all levels should be properly divided, and the relationship between market participation and government supervision should be further coordinated. On the other hand, to reduce institutional fiscal pressure, a stable financial security system for local governments should be built to narrow the gap between revenue and expenditure through transfer payments and tax rebates. The local financial departments should raise the fiscal fund allotment for the management of emission rights trading, including the relevant expenditures in the unified arrangement of the financial budget.
(3) Enterprises should be encouraged to drive up profits through emission reduction, which leads to a positive cycle. In order to incentivize enterprises to voluntarily reduce emissions, a market mechanism combined with appropriate government intervention should be employed to further widen the gap between costs of emitting and the benefits of abatement. To accomplish reduction goals at given output levels, enterprises can apply operating leverage reasonably and effectively, allocating the capital investment and cost structure of emission reduction technology from a long-term perspective. Since economic benefits come later than the abatement effect, industrial enterprises need to be effectively guided to smoothly pass through the period of stagnant profit growth.

6.3 Limitations and further research

The conclusion of this paper is convincing, nevertheless, there exist certain limitations that necessitate further research to address. On the one hand, given that pollutants may be transmitted between adjacent cities and redistributed based on cross-city parent-subsidiary company relationships, it is necessary to consider both the spillover effect of policy implementation and pollution transfer. Solving this problem necessitates access to pollution data from enterprises, which can be procured through the China Industrial Enterprise Pollution Database (CIEPD). However, the operational status of industrial enterprises in CIEPD is discontinuous and does not provide information on subsidiary companies or their geographical locations. If listed companies are taken as samples, the types and units of pollutants disclosed are not uniform. As big data continues to be widely used, this problem may be solved in the future. On the other hand, to illustrate how local fiscal pressure affects the effectiveness of ETS, we theoretically analyze the possible pathways (quota allocation, excess emission fines, and transaction costs). We highlight the importance of addressing institutional fiscal pressure. Nevertheless, further research is necessary to provide more empirical evidence and specific measures for mitigating institutional fiscal pressure.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

YS contributed to study design, data analysis, and draft writing. YS and XG contributed to data curation and visualization. YS, HH, and QC contributed to revisions and proofreading. HH contributed to funding acquisition, project administration, and resources. All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

Funding

This study was supported by the National Social Science Fund of China (No. 18BTJ001 and No. 20XTJ005) and the Central Government Funds for Guiding Local Science and Technology Development (No. GSK215115).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2023.1095321/full#supplementary-material

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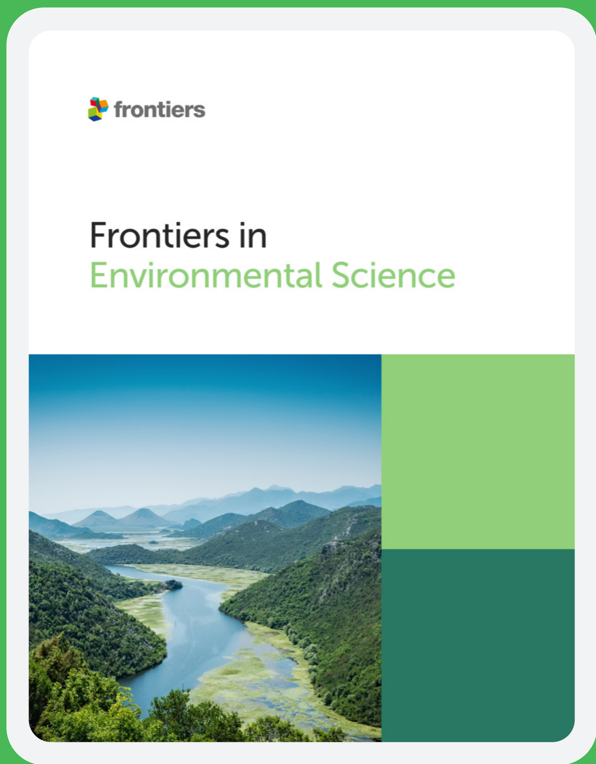

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