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Measurement and enhancement paths of ecological civilization construction in karst regions of Southwest China

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Introduction: Karst regions in Southwest China are ecologically fragile and face complex governance challenges during rapid socio-economic transformation. Clarifying the evolutionary characteristics and governance constraints of ecological civilization construction in these regions is critical for promoting sustainable development and precision governance.

Methods: This study developed a multidimensional evaluation framework comprising 29 indicators to assess ecological civilization construction in typical karst regions. Using Guizhou Province as a case study, construction levels were systematically measured at the provincial, municipal, and county scales for three key temporal nodes (2012, 2018, and 2023). Spatial autocorrelation models were applied to reveal spatio-temporal differentiation patterns and spatial dependence characteristics.

Results: The results show that from 2012 to 2023, the comprehensive ecological civilization index in Guizhou Province increased significantly, with an average annual growth rate of 10.02%, indicating the effectiveness of the green transition during the modernization process. However, pronounced spatial non-equilibrium persists, forming a county-level pattern characterized by “high-value clustering in the southeast and low-value clustering in the west,” accompanied by a continuously strengthening positive spatial autocorrelation.

Discussion: Further analysis reveals that the observed spatial disparities are driven by deep-seated mechanisms, including governance cost differentials imposed by karst habitat constraints, path dependency of resource-based industries, and cultural disconnection during rapid urbanization. These findings provide a theoretical basis for differentiated and precision-oriented governance strategies in ecologically fragile regions and offer a valuable “China Solution” for achieving global sustainable development goals in similar karst environments.

KEYWORDS

comprehensive evaluation index, ecological civilization construction, improvement path, karst regions, level measurement

1 Introduction

Ecological civilization is not merely an isolated policy concept but a localized manifestation of the global “strong sustainability” paradigm. Its core logic underscores the non-substitutability of natural capital and the binding constraints imposed by ecological redlines (Costanza et al., 2017). This conceptualization is highly aligned with the United Nations Sustainable Development Goals (SDGs), the OECD Green Growth Indicator System, and the World Bank’s Green Growth Framework, particularly in their shared objectives of safeguarding resource efficiency and environmental quality (Sachs et al., 2019). “Promote green development and advance the harmonious coexistence of humans and nature” (Center, 2022); the concept of green development in the new era serves not only as the core ideology guiding the green and low-carbon transformation of the economy and society, but also as a key principle for taking the path of Chinese-style modernization (Tang, 2023). Currently, against the backdrop of the coordinated advancement of the “dual carbon” goals and high-quality development, the construction of ecological civilization has become an indispensable path to resolve the contradiction between development and protection and realize the comprehensive green transformation of the economy and society, and its strategic position in the process of Chinese-style modernization has become increasingly prominent. It breaks the path dependence of the traditional “development first, governance later” model, transforming the relationship between ecological environmental protection and economic and social development from an “opposing relationship” to a “symbiotic relationship” (Hao et al., 2025), thereby providing a Chinese solution to the challenges of global development and environmental governance. Within this global framework of sustainable development, the practical dimensions of ecological civilization construction have expanded from the establishment of national ecological security barriers to the cultivation of distinctive regional eco-economies (Wang et al., 2025; Yu et al., 2025) — especially for regions with fragile ecological backgrounds but prominent ecological values (Rong et al., 2025), how to identify construction shortcomings through scientific level measurement and release ecological advantages through precise improvement paths (Wei et al., 2022) has become a core issue in promoting regional coordinated development and practicing the concept of green development. This is not only related to the ecological security and economic transformation of local areas, but also closely linked to the overall advancement of the national ecological civilization strategy and the comprehensive realization of Chinese-style modernization, which holds important theoretical value and practical significance (Xin et al., 2023; Yuan, H et al., 2025).

As one of the first batch of national ecological civilization pilot zones in China, Guizhou Province is located in the important ecological barrier area of the upper reaches of the Yangtze River and the Pearl River. Its ecological environment not only directly determines the quality of regional sustainable development (Hu, 2022), but also plays an irreplaceable strategic role in maintaining the national ecological security pattern (Zhu et al., 2024). However, deep-seated issues such as the inherent ecological vulnerability of karst landforms and unbalanced regional economic development still restrict the in-depth advancement of ecological civilization construction (Guo et al., 2013), and have become a core bottleneck

affecting the stable restoration and sustainable development of the regional ecosystem (Song et al., 2014). In recent years, Guizhou Province has promoted the construction of ecological civilization based on its regional reality, and achieved remarkable results in ecological restoration (Sun et al., 2025) and green industry cultivation (Yang and He, 2024): through innovative practices such as the implementation of comprehensive rocky desertification control projects (Hu 2024) and the establishment of an ecological compensation mechanism for the Chishui River Basin (Zhou et al., 2018), it has initially explored a characteristic path of coordinated progress in “ecological protection—economic development”. A review of existing studies shows that the academic community has conducted extensive research on the construction of theoretical frameworks and macro-policy analysis for ecological civilization construction (Cheng and Peng, 2022), but there are still obvious gaps in empirical research on ecologically fragile areas—especially in terms of the systematic measurement of the level of ecological civilization construction in Guizhou Province and the analysis of its dynamic evolution characteristics, relevant achievements are relatively scarce (Zhao et al., 2024). At the same time, in the new context of Chinese-style modernization, how to quantify the level of ecological civilization construction through scientific methods, accurately identify development shortcomings, and propose operable improvement paths in line with regional characteristics has become a practical issue that urgently needs to be addressed (Wang, 2018).

Consequently, addressing the practical needs of ecological civilization in Guizhou, this research constructs a multidimensional index system aligned with the SDGs. By integrating the Ecological Quality Index (EQI), species richness, and ecosystem cultural service values, the study quantitatively reveals the status and evolutionary dynamics of ecological civilization, proposing targeted promotion strategies. The objective is to reflect the unique features of karst regions and identify regional heterogeneities and vulnerabilities. This study not only offers a scientific foundation for targeted interventions and the maximization of ecological advantages in Guizhou but also serves as a global reference for the spatial governance and performance measurement of ecologically fragile areas under the framework of sustainable development.

2 Study area and methodology

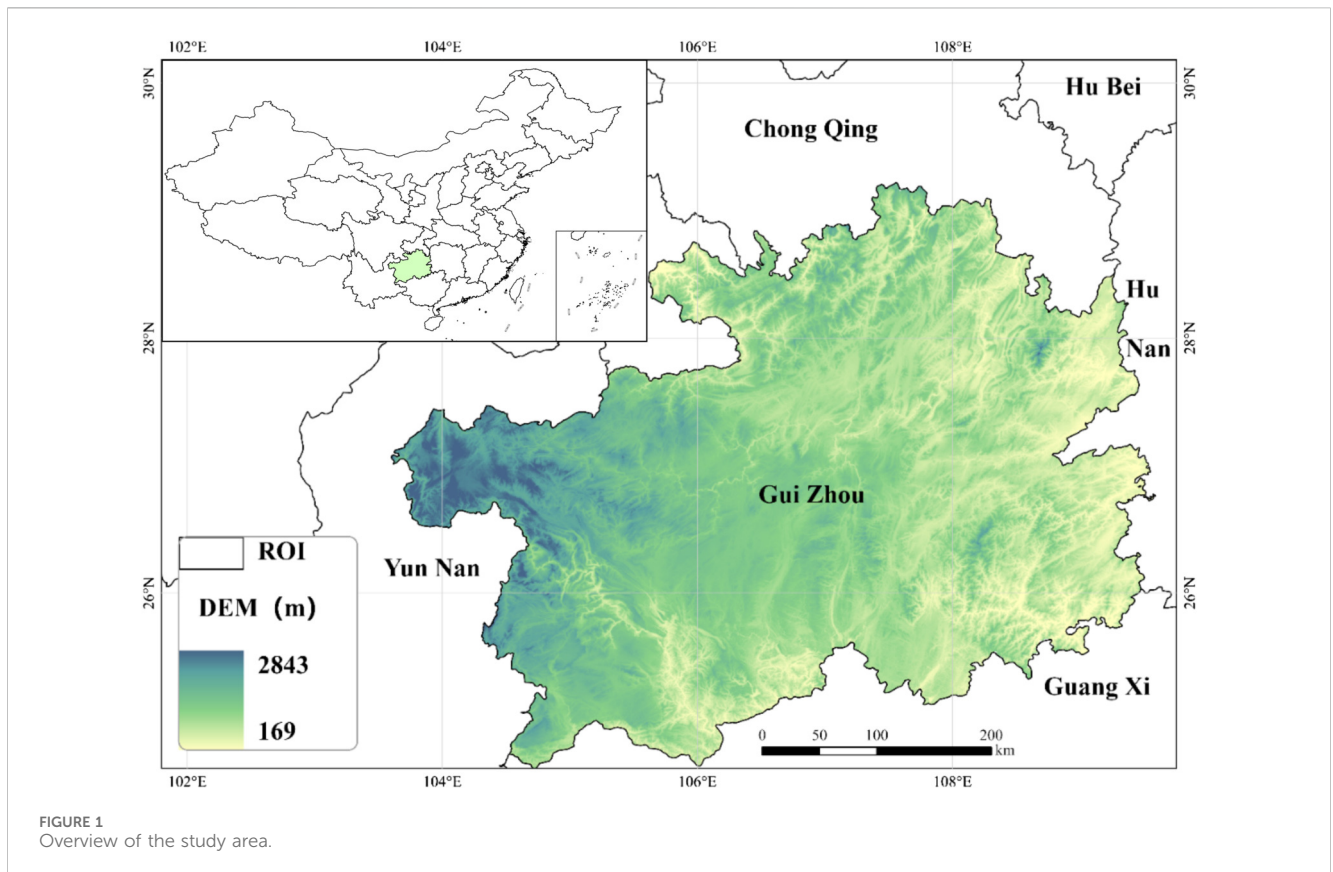
2.1 Study area overview

Located in the center of the karst landscape of Southwest China, Guizhou Province (103°36′–109°35′E, 24°37′–29°13′N) is characterized by diverse geomorphology, including plateaus, mountains, hills, and basins. As shown in Figure 1, karst landforms cover as much as 61.9% of the provincial territory (Liu, 2021).

2.2 Construction of the index system

2.2.1 Selection of time nodes

Three time nodes—2012, 2018, and 2023—were selected. 2012 marked the initial year when ecological civilization construction was elevated to a national strategy, and Guizhou



had already carried out a number of related practices prior to that; 2018 was a critical period for policy implementation, with a series of policies being put into effect; 2023 reflects the construction progress in the new stage of Chinese-style modernization. These three time nodes can effectively demonstrate the effect of policy implementation and development dynamics.

2.2.2 Construction of the evaluation index system

The index system adheres to the principles of scientificity, systematicness, operability, independence, orientation, and consistency to ensure that it accurately reflects the essence of ecological civilization construction, comprehensively covers all aspects of the construction, and includes indicators that are mutually independent and have clear orientations, which can effectively guide the practice of ecological civilization construction.

Closely aligned with the requirements of the ecological civilization system reform under Chinese-style modernization, indicators such as green development (energy consumption, carbon emissions, etc.), ecological agriculture (fertilizer and pesticide usage), ecological protection red lines, and biodiversity (species richness of animals and plants) were incorporated into the system. Emphasis was placed on the coordinated advancement of the economy and ecology, and the accounting methods for the value of ecological products were enriched, providing a new perspective for the evaluation of ecological civilization construction in Guizhou.

With reference to relevant national and local index systems, 29 indicators were selected from four dimensions (ecological security, ecological economy, ecological culture, and ecological

civilization institutions) to construct the evaluation system, as presented in [Table 1](#). Compared with previous studies, a number of new indicators were added. Although the number of county-level indicators was reduced due to data limitations, the system can still comprehensively evaluate the level of ecological civilization construction in Guizhou Province.

2.3 Data standardization and weight determination

2.3.1 Data sources

This study took the data of Guizhou Province, its 9 prefecture-level cities/autonomous prefectures, and 88 districts/counties in 2012, 2018, and 2023 as samples. The data for various indicators were sourced from provincial industrial departments, China Statistical Yearbook, Provincial Statistical Yearbooks, the EPS Data Platform, and the China Environmental Protection Database.

Map Data Source: The map data used in this study were all derived from the standard map with map review number GS (2024) 0650, downloaded from the National Geospatial Information Public Service Platform (Tianditu). The base map remains unmodified.

2.3.2 Handling of missing indicator data

To address the issue of missing data for certain years and regions, the decision tree imputation method was employed via SPSSPRO software. Specifically, this approach was used to impute

TABLE 1 Weights of evaluation indicators for ecological civilization construction level.

Target layer	Criterion layer	Weight	No.	Indicator layer	Weight
Ecological security	Ecological environment quality	0.25	1	Proportion of days with good air quality in central cities	0.10
			2	PM2.5 concentration reduction rate	0.08
			3	Proportion of centralized drinking water sources with water quality reaching or exceeding class III	0.13
			4	Urban domestic sewage treatment rate	0.17
			5	Urban domestic waste harmless treatment rate	0.24
			6	Ecological quality index	0.28
	Ecosystem stability	0.15	7	Proportion of nature reserves in land area	0.12
			8	Proportion of ecological protection red line area	0.14
			9	Plant species richness	0.09
			10	Animal species richness	0.06
			11	Forest coverage rate	0.33
			12	Forest stock volume	0.26
Ecological economy	Green development	0.20	13	Energy consumption per unit of GDP	0.20
			14	Electricity consumption per unit of GDP	0.20
			15	Carbon dioxide emission reduction rate per unit of regional GDP	0.15
			16	Carbon sequestration capacity	0.20
			17	Agricultural chemical fertilizer application amount	0.10
			18	Pesticide application amount	0.15
	Resource conservation and intensification	0.15	19	Comprehensive utilization rate of general industrial solid waste	0.31
			20	Water consumption per 10,000 yuan of GDP	0.15
			21	Per capita water consumption	0.13
			22	Per capita water resources	0.16
			23	Construction land area per unit of regional GDP	0.25
Ecological Culture Culture	Ecological culture value	0.10	24	Number of ecological culture demonstration bases	0.50
			25	Cultural service value of ecosystems	0.50
	Universal sharing and Co-construction	0.05	26	Green coverage rate in built-up areas	0.50
			27	Per capita park green space area	0.50
Ecological civilization institutions	Institutional guarantee	0.10	28	Total number of current local environmental protection laws and regulations	0.50
			29	Number of environmental protection system institutions	0.50

missing values for the “pesticide application amount” indicator in Tongren and Bijie for the year 2012.

Standardization can effectively eliminate dimensional differences between indicators and enhance the comparability of different indicators. In this study, the commonly used standardization formula was applied, as shown in Equation 1.

$$X_{ij} = \frac{x_{ij} - \mu_j}{\sigma_j} \tag{1}$$

Where μ represents the mean value of each indicator, and σ represents the standard deviation of each indicator.

In addition, considering that the indicator system includes both positive and negative indicators, normalization of each indicator was necessary to ensure consistent directions and comparability of all indicators. For details, refer to Equations 2, 3:

$$\text{For positive indicators: } X_{ij} = \frac{x_{ij} - \min(x_{ij})}{\max(x_{ij}) - \min(x_{ij})} \tag{2}$$

$$\text{For negative indicators: } X_{ij} = \frac{\max(x_{ij}) - x_{ij}}{\max(x_{ij}) - \min(x_{ij})} \tag{3}$$

TABLE 2 Ecological civilization construction level of Guizhou province (2012–2023).

Year	2012	2018	2023
Comprehensive index of ecological civilization construction	0.3162	0.5770	0.9038
Average annual growth rate	10.02%		

2.3.3 Determination of indicator weights

Utilizing SPSSPRO software, judgment matrices were constructed from the normalized data using the Analytic Hierarchy Process (AHP). The validity of these matrices was confirmed by passing the consistency test with a Consistency Ratio (CR) of less than 0.1, after which the final weights were derived. According to Table 1, the weights for ecological security (0.40) and ecological economy (0.35) are relatively high, aligning with the principle of prioritizing ecology in the assessment. The weights of ecological culture and ecological civilization institutions are 0.15 and 0.10 respectively. For the county-level evaluation, three indicators—pesticide application amount, total number of effective local environmental regulations, and number of environmental protection system institutions—were excluded due to data limitations.

2.4 Calculation method of the ecological civilization construction level index

2.4.1 Synthesis of the ecological civilization construction level index

The Ecological Civilization Construction Level Index was calculated using the linear weighted synthesis method. The data were processed through normalization and standardization, as shown in Equation 4:

$$ECI = \sum_{i=1}^p W_i X_i \tag{4}$$

Where ECI denotes the ecological civilization construction level index, W represents the weight of each indicator determined by AHP, and X stands for the normalized data of each indicator.

2.4.2 Calculation of the average annual growth rate

Based on the geometric average growth rate formula, the average annual change trend of the indicator data from 2012 to 2023 was calculated, as shown in Equation 5:

$$r = \left[\left(\frac{A_n}{A_1} \right)^{\frac{1}{n-1}} - 1 \right] \times 100\% \tag{5}$$

where r is the average annual growth rate, A_n is the current-period data, and A_1 is the data of the starting year among the previous n years. This formula calculates the average annual growth rate, which represents an average annual growth speed rather than the total cumulative growth speed.

3 Results analysis

3.1 Measurement of the ecological civilization construction level index in Guizhou Province

3.1.1 Analysis of the ecological civilization construction level measurement (Guizhou Province)

According to the calculation method of the ecological civilization construction level index, the weighted sum of each indicator was calculated in accordance with the hierarchical relationship of “target layer - criterion layer - indicator layer,” and the ecological civilization construction level indexes of Guizhou Province in 2012, 2018, and 2023 were obtained. The specific results are shown in Table 2.

The measurement results show that the ecological civilization construction level index of Guizhou Province exhibited a continuous upward trend from 2012 to 2023, reflecting the phased improvement of regional ecological governance effects. From a phased perspective:

Development stage (2012–2018): Driven by the dual engines of strengthened ecological protection investment and pollution control, three significant progresses were achieved. Firstly, the implementation of forest resource conservation projects led to a phased increase in forest coverage rate and an improvement in the carbon sequestration capacity of the ecosystem. Secondly, the promotion of clean production technologies in the industrial sector and the establishment of an energy conservation and emission reduction assessment mechanism resulted in a continuous decline in energy consumption per unit of GDP and the emission intensity of major pollutants. Thirdly, the construction of a river basin water environment protection system and the promotion of pollution control in key rivers and lakes significantly improved the comprehensive water environment quality index.

Deepening stage (2018–2023): The governance model was extended to institutional innovation and industrial transformation and upgrading. The ecological environment supervision system was further improved, with the establishment of an inter-departmental collaborative law enforcement mechanism and an ecological protection red line system to enhance the legalization level of environmental governance. The green industrial system was accelerated, with policy guidance promoting the green transformation of traditional industries and the growth of strategic emerging industries such as new energy and eco-tourism, realizing the decoupling of economic growth from resource consumption. Major projects such as mine ecological restoration, wetland protection, and rocky desertification control were launched, gradually restoring the ecological functions of

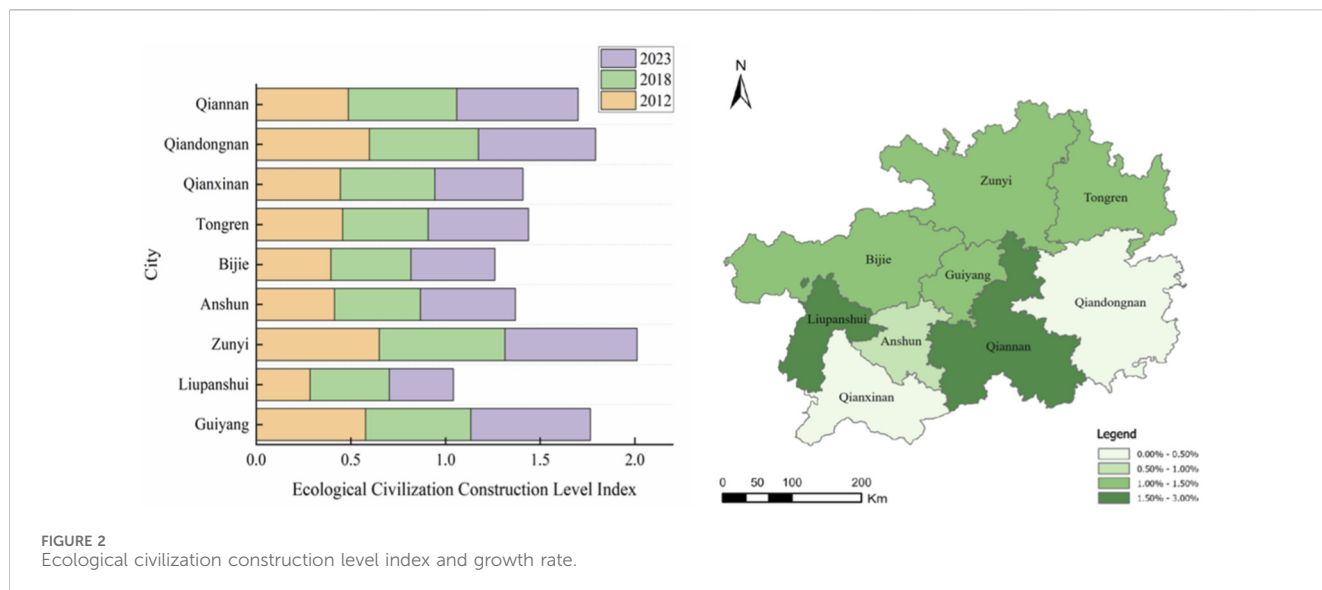


FIGURE 2 Ecological civilization construction level index and growth rate.

ecologically fragile areas and optimizing the regional ecological security pattern.

3.1.2 Analysis of the ecological civilization construction level measurement (prefecture-level cities/autonomous prefectures)

The calculation method of the ecological civilization construction level index for each prefecture-level city/autonomous prefecture was the same as above, and the final comprehensive indexes of ecological civilization construction for each prefecture-level city/autonomous prefecture in Guizhou Province are shown in Figure 2.

The data show that by 2018, the indexes of Qiandongnan Miao and Dong Autonomous Prefecture, Guiyang City, and Tongren City had decreased compared with the base year 2012, but the overall trend was upward. The main reason for this, as analyzed, is that the evaluation value of the ecological economy indicator in 2018 among the sub-target layers in these regions was lower than that in other prefecture-level cities/autonomous prefectures, leading to certain fluctuations.

From 2012 to 2023, the ecological civilization construction of various prefecture-level cities/autonomous prefectures in Guizhou Province showed significant spatial heterogeneity and dynamic evolution characteristics. Time-series analysis reveals that the indexes of Qiandongnan Miao and Dong Autonomous Prefecture, Guiyang City, and Tongren City in 2018 experienced a phased decline compared with 2012, mainly due to the evaluation value of the ecological economy indicator being lower than the provincial average. Although Liupanshui City and Qianxinan Buyei and Miao Autonomous Prefecture showed an overall upward trend, their indexes in 2023 fell compared with 2018. The former was affected by the deterioration of ecological security indicators (such as the number of days with good air quality in central cities and sewage treatment rate), while the latter was due to the continuous increase in the proportion of the secondary industry (reaching 33.0% in 2023), resulting in fluctuations in ecological economy indicators.

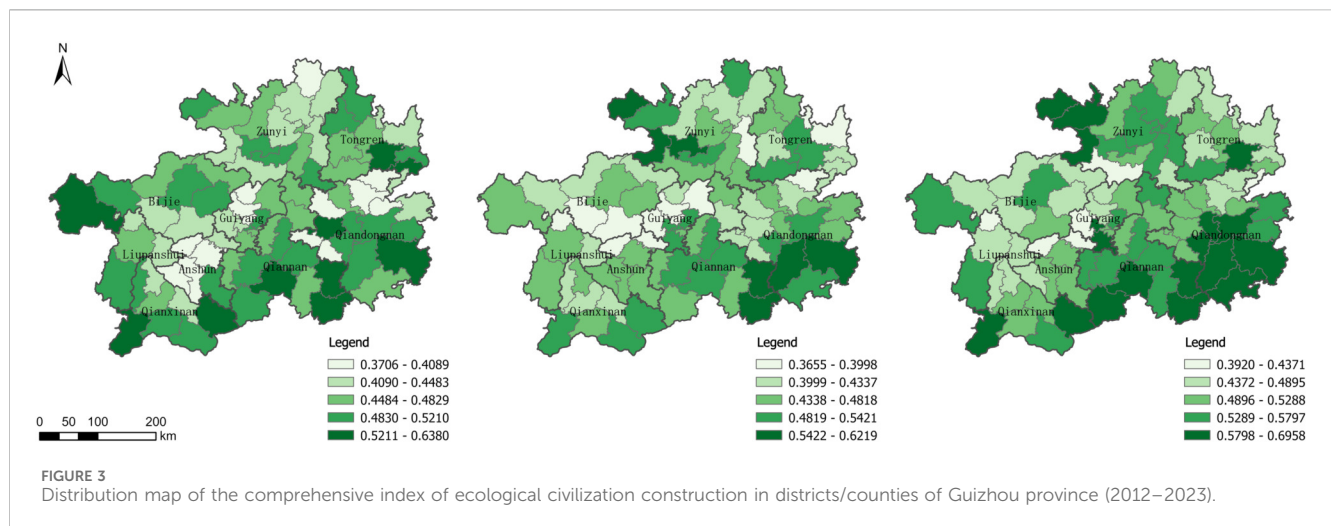
A horizontal comparison of the 2023 comprehensive indexes shows that Zunyi City (0.6988), Qiannan Buyei and Miao

Autonomous Prefecture (0.6413), and Guiyang City (0.6324) ranked among the top three, demonstrating strong ecological governance efficiency. Qianxinan Buyei and Miao Autonomous Prefecture (0.4654), Bijie City (0.4442), and Liupanshui City (0.3387) had relatively low indexes and faced greater pressure for improvement. The average annual growth rate in Figure 2 indicates that Qiannan Buyei and Miao Autonomous Prefecture (the highest) and Qiandongnan Miao and Dong Autonomous Prefecture (the lowest) formed a polarization, reflecting significant differences in regional governance models and resource endowments.

From the perspective of individual prefecture-level cities/autonomous prefectures: Qiannan Buyei and Miao Autonomous Prefecture achieved both excellent growth rate and index through the coordinated development strategy of ecological protection and green industries; Anshun City maintained a steady development trend; Liupanshui City, as a traditional industrial city, needs to accelerate ecological restoration and industrial transformation to reverse the backward situation; leading regions such as Guiyang and Zunyi should focus on model innovation and resource optimization allocation to play a demonstration role; while Qianxinan Buyei and Miao Autonomous Prefecture and Bijie City need to address the bottlenecks of funds and technology and learn from advanced experiences to promote ecological civilization construction. In general, narrowing regional gaps and strengthening policy coordination will become the key paths for the high-quality development of ecological civilization construction in Guizhou Province.

3.1.3 Analysis of the ecological civilization construction level measurement (districts/counties)

The calculation method of the ecological civilization construction level index for each district/county was the same as above, and the final distribution map of the comprehensive indexes of ecological civilization construction for each district/county in Guizhou Province is shown in Figure 3. It can be concluded that the



ecological civilization construction of each district/county in Guizhou Province has improved year by year. From the overall trend, the median index of all districts/counties in the province in the base year 2012 was 0.4703, and there were 44 districts/counties with indexes lower than this value in 2012. By 2023, the number of districts/counties with indexes lower than this value had decreased to 17. This indicates that the level of ecological civilization construction was relatively low in the early stage, and from 2018 to 2023, the level of ecological civilization construction achieved a significant overall improvement compared with the base year data. In particular, the ecological civilization construction indexes of regions such as Libo County, Leishan County, Rongjiang County, Huaxi District, Pingtang County, Wangmo County, Guanshanhu District, Sandu County, Jiangkou County, Renhuai City, and Chishui City increased significantly, reaching above 0.6121, and became advanced regions in ecological civilization construction. However, a small number of counties, such as Pingba District, Puding County, Yuping County, and Zhongshan District, developed relatively slowly with low ecological civilization construction indexes and still require further improvement. Overall, the level of ecological civilization construction in Guizhou Province has been significantly improved, regional development has become increasingly balanced, and the gap between some backward districts and counties has gradually narrowed.

To further analyze the statistical significance of the evaluation data, SPSSPRO software was used to conduct descriptive statistical analysis, obtaining the data characteristics, distribution patterns, and centralization and dispersion of relevant observation indicators from 2012 to 2023. This helps to gain an in-depth understanding of the change trends of the evaluation values in different years.

The results show that the ecological civilization construction of districts/counties in Guizhou Province presents a trend of “total improvement, expanded differences, and optimized structure”. The overall level was significantly improved in 2023, but some districts/counties still lagged behind. It is necessary to target the strengthening of ecological investment and coordinated development mechanisms in underdeveloped regions.

3.2 Analysis of the evaluation indicators for ecological civilization construction in Guizhou Province

3.2.1 Ecological security

The changes in the index of each evaluation indicator are shown in Figure 4.

3.2.1.1 Provincial ecological security

The ecological security index increased significantly, with remarkable results in systematic governance. From 2012 to 2023, the ecological security index of Guizhou Province jumped from 0.1449 to 0.3932, increasing by nearly 2.7 times in 12 years. The ecological environment quality index and system stability index rose simultaneously (from 0.1044 to 0.0405 to 0.2500 and 0.1432 respectively). This is attributed to the delineation of ecological red lines and strict management of key ecological function zones at the policy level, the strict control of pollution sources and improvement of water source areas in water quality management, and the comprehensive greening project that increased the forest coverage rate from 46.96% to 63.00%. These multiple measures have promoted the comprehensive optimization of the ecological security system.

3.2.1.2 Prefecture-level ecological security

There was significant regional differentiation, with both advantages and challenges coexisting. In 2023, the ecological security index of each prefecture-level city/autonomous prefecture showed a pattern of “leading in the southeast and differentiation in the central and western regions”: Qiandongnan Miao and Dong Autonomous Prefecture (0.3727), Zunyi City (0.3202), and Qiannan Buyei and Miao Autonomous Prefecture (0.3108) ranked among the top relying on eco-tourism, green industries, and urban ecological construction; Liupanshui City (0.1506) saw a decline in air quality and sewage treatment indicators due to the coal industry, and Anshun City (0.2409) experienced a short-term decline in air quality in 2018. However, both cities still had highlights in indicators such as waste treatment

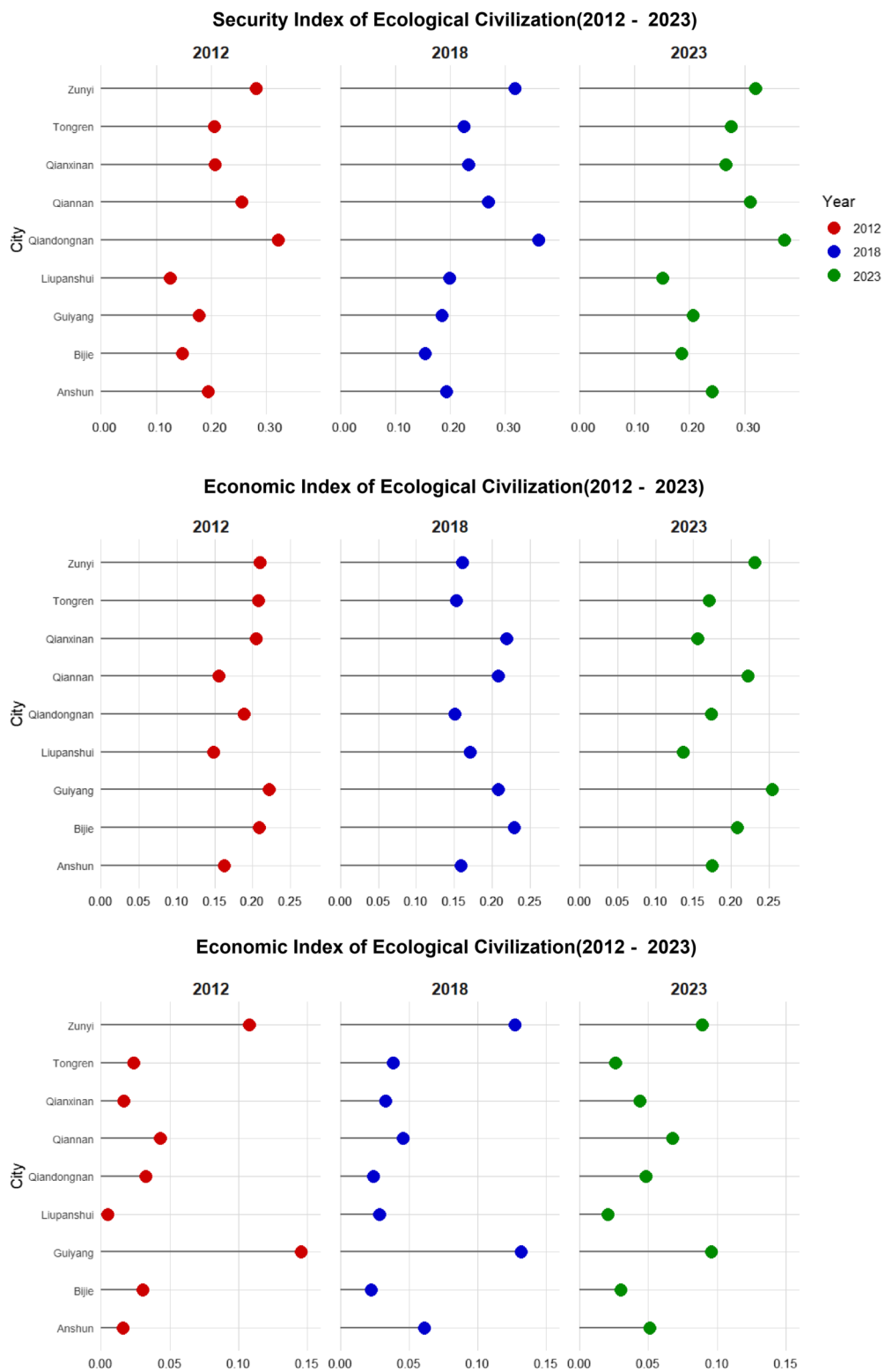


FIGURE 4 Ecological security, economy, and culture indexes (2012–2023).

and forest stock volume, reflecting the in-depth contradiction between industrialization and ecological protection.

3.2.1.3 District-level ecological security

The spatial distribution was uneven, with high-value agglomeration in the southeast. The 2023 district-level ecological security index shows that high-value regions (top 10) are concentrated in Qiandongnan and Qiannan, such as Libo County and Leishan County, which achieved leading indexes through ecotourism and ethnic cultural protection; low-value regions (bottom 10) are mostly distributed in the central and western regions. For example, Qixingguan District and Zhongshan District are affected by industrialization and urbanization, facing problems such as poor air quality (the proportion of days with good air quality in some districts/counties is insufficient), backward sewage treatment capacity (Jinping County and other regions <95%), and low forest coverage rate (Yunyan District is about 40%), showing obvious characteristics of unbalanced regional development.

3.2.1.4 Key indicators and future directions

There are both advantages and shortcomings, and it is necessary to strengthen balanced governance. The province's centralized drinking water source quality has achieved 100% compliance with standards, and the harmless treatment rate of domestic waste has reached 99.68%, demonstrating the basic advantages of ecological governance. However, the forest coverage rate of 6 prefecture-level cities/autonomous prefectures including Guiyang is lower than the provincial average, the ecological system stability of Liupanshui City and Bijie City is affected by the inter-annual fluctuation of forest resources, and some districts/counties have insufficient sewage treatment capacity. In the future, it is necessary to focus on the backward central and western regions, promote green industrial transformation, precise pollution control, and forest resource protection, break the bottleneck of "local optimization and global imbalance", and realize the balanced improvement of ecological security from quantity to quality.

3.2.2 Ecological economy

3.2.2.1 Provincial ecological economy

The index generally rose but with significant fluctuations, and the resource utilization efficiency needs to be improved. From 2012 to 2023, the ecological economy index of Guizhou Province increased from 0.1501 to 0.2740, showing an upward trend. However, the resource conservation and intensification index in 2018 decreased compared with 2012, reflecting development fluctuations. The green development index jumped from 0.0340 to 0.1734, while the resource conservation and intensification index declined briefly in 2018 due to the decrease in the comprehensive utilization rate of general industrial solid waste and the increase in *per capita* water consumption, and rose back to 0.1006 in 2023. In 2023, the energy consumption per unit of GDP was 0.54 tons of standard coal per 10,000 yuan, lower than the national average but higher than that of Yunnan and Chongqing; the carbon dioxide emission reduction rate was 2.40%, lower than the national 5.67%; the water consumption per 10,000 yuan of GDP was 44.6 m³ per 10,000 yuan, slightly lower than the national average. These data indicate that the growth of the ecological economy is still restricted by resource utilization efficiency and low-carbon transformation.

3.2.2.2 Prefecture-level ecological economy

There was obvious differentiation, and some regions lagged in transformation. In 2023, only 5 prefecture-level cities/autonomous prefectures including Guiyang (0.2536) and Zunyi (0.2312) had an ecological economy index higher than that in 2012. Liupanshui City (0.1363) and Qianxinan Buyei and Miao Autonomous Prefecture (0.1559) showed a downward trend due to high energy consumption per unit of GDP (1.10 tons per 10,000 yuan in Liupanshui), excessive electricity consumption (1801.10 kWh per 10,000 yuan in Qianxinan), and insufficient carbon dioxide emission reduction (0.56% in Anshun). In the green development index, Guiyang (0.1515) and Qiandongnan (0.1367) took the lead; in the resource conservation and intensification index, Guiyang (0.1020) and Qiannan (0.0944) performed well. However, Liupanshui (0.0530) and Qiandongnan (0.0374) ranked low due to low water resource utilization efficiency and insufficient comprehensive utilization of industrial solid waste, showing significant differences in low-carbon transformation and resource management capabilities among regions.

3.2.2.3 District-level ecological economy

High-value agglomeration was observed in the southeast, and prominent energy consumption bottlenecks existed in the northwest. In 2023, the district-level ecological economy index was the highest in Renhuai (0.2731) and Wangmo (0.2680), with high-value regions concentrated in the southeast. In the northwest, regions such as Zhongshan District and Bozhou District had low indexes due to energy consumption per unit of GDP exceeding 1 ton per 10,000 yuan (8 districts/counties including Qingzhen and Kaiyang >1) and carbon dioxide emission reduction failing to meet the national level (only 10 districts/counties met the standard). In terms of the comprehensive utilization rate of industrial solid waste, 5 districts/counties in Tongren were lower than the national average; in water resource management, the *per capita* water consumption in Hezhang, Bijie was only 93 m³ per person (less than 25% of the national average), and the water consumption per 10,000 yuan of GDP in Guanshanhu District, Guiyang was 10.48 m³ per 10,000 yuan, performing excellently. However, the *per capita* water resources in Yunyan and Nanming were as low as double digits, reflecting the unbalanced development caused by resource endowments and industrial structures among districts/counties.

3.2.3 Ecological culture

3.2.3.1 Provincial ecological culture

The index continued to rise but had a weak foundation, with obvious shortcomings in demonstration and greening. From 2012 to 2023, the ecological culture index of Guizhou Province increased from 0.0167 to 0.1365, with both the ecological culture value (0.0865) and universal sharing and co-construction (0.0500) dimensions increasing simultaneously. The number of ecological culture demonstration bases increased from zero to 21, but the quantity was still less than that of Sichuan (47) and Yunnan (29). In 2023, the green coverage rate in built-up areas was 41.92%, lower than the national 43.32%, reflecting the gap between the hardware foundation of ecological culture in Guizhou and that of other western provinces.

3.2.3.2 Prefecture-level ecological culture

The core cities fluctuated downward, and there was significant differentiation in regional sharing and co-construction. In 2023, the ecological culture index of Guiyang (0.0957), Zunyi (0.0891), and Qiannan Buyei and Miao Autonomous Prefecture (0.0673) ranked among the top. However, compared with 2012, Guiyang and Zunyi decreased by 34.3% and 17.3% respectively, mainly due to the decline in the cultural service value of the ecosystem and the green coverage rate in built-up areas; Liupanshui City (0.0202) had the lowest index in the province, with both weak ecological culture value and sharing and co-construction capabilities. In the universal sharing and co-construction index, Anshun City (0.0449) jumped to the first place due to the improvement of greening indicators, while Zunyi City saw a decline in the index due to insufficient *per capita* park green space, showing prominent differences in the investment and effectiveness of ecological culture construction among regions.

3.2.3.3 District-level ecological culture

High-value agglomeration was in the central and northern regions, and shortcomings in demonstration and greening restricted balance. In 2023, the district-level ecological culture index was the highest in Huaxi District, Guiyang (0.0861), with high-value regions concentrated in the central and northern regions (such as Chishui and Renhuai), and low-value regions mostly distributed in the northwest and southern regions (such as Hezhang and Congjiang). Among the 88 districts/counties in the province, 46 had no ecological culture demonstration bases, and only 14 had a green coverage rate in built-up areas higher than the national average. Xifeng County (28.81%) and Hezhang County (7.70 m² of *per capita* park green space) had obvious shortcomings, reflecting significant spatial imbalance in the construction of ecological culture infrastructure at the district-county level, and the need to strengthen the popularization of ecological culture at the grassroots level and the service capacity of green spaces.

3.2.4 Ecological civilization institutions

3.2.4.1 Provincial ecological civilization institutions

The index increased significantly from a low base, and the policy support system developed from weakness to strength. From 2012 to 2023, the ecological civilization institution index of Guizhou Province surged from 0.0045 to 0.1000, increasing by more than 20 times in 12 years, reflecting the rapid development of institutional construction from the initial stage to systematization. The “institutional guarantee” index at the criterion layer rose simultaneously, confirming the remarkable achievements in the implementation of ecological policies, improvement of the legal system, and construction of management mechanisms since 2012, which provides basic support for the ecological civilization construction of the whole province.

3.2.4.2 Prefecture-level ecological civilization institutions

Most regions made progress while some experienced regression, and regional coordination needs to be strengthened. The 2023 data show that 6 prefecture-level cities/autonomous prefectures including Guiyang (0.0774),

TABLE 3 Global Moran's I index of spatial autocorrelation.

Year	Moran I index	Variance (VAR)	P-value
2012	0.2067	0.0060	0.0048
2018	0.2995	0.0060	0.0000
2023	0.3345	0.0060	0.0000

Liupanshui (0.0316), and Tongren (0.0575) had a significant increase in the institution index compared with 2012, among which Guiyang had the fastest growth rate in institutional construction relying on the resource advantages of the provincial capital. However, Anshun (0.0350), Qiandongnan (0.0246), and Qianxinan (0.0000) experienced a decline, and Qianxinan even dropped to 0, exposing serious shortcomings in the implementation of ecological institutions and policy continuity in some regions. The province has 91 current local environmental protection laws and regulations, which is less than that of Yunnan (100) and Sichuan (about 70), indicating that there is still room for improvement in the completeness and implementation efficiency of the legal system.

3.3 Analysis of spatial agglomeration of ecological civilization construction level

3.3.1 Global spatial autocorrelation analysis

Global spatial autocorrelation describes the characteristics of the ecological civilization construction level in the entire district/county space. This study adopted the global Moran's I index and used ArcGIS software to test the global spatial autocorrelation of the ecological civilization construction level of 88 districts/counties in Guizhou Province in 2012, 2018, and 2023. The test results of the global Moran's I index for the ecological civilization construction level are shown in Table 3.

To avoid redundancy caused by excessive repeated content, only the 2023 Moran's I report of the ecological civilization construction index is presented in the paper, as shown in Figure 5. A Moran's I > 0 indicates positive spatial correlation, and the larger the value, the more obvious the spatial correlation; a Moran's I < 0 indicates negative spatial correlation, and the smaller the value, the greater the spatial difference; otherwise, Moran's I = 0, indicating random spatial distribution. A P-value less than 0.05 indicates that the result is statistically significant, meaning there is significant spatial autocorrelation in the spatial data; a small variance (VAR) indicates small variation in the Moran's I index and stable data. Combined with the content of the figure, the P-values and variances of the sample data in the 3 years all meet the requirements and pass the significance test.

The results show that the ecological civilization construction level of Guizhou Province at the three important time nodes of 2012, 2018, and 2023 showed strong spatial correlation in space, which also indicates that there is mutual influence on the ecological civilization construction level among different districts/counties in Guizhou Province. The Moran's I index of the ecological civilization construction level is all greater than 0.25, indicating that there is positive spatial correlation in the ecological civilization construction level of each district/county in space, and districts/

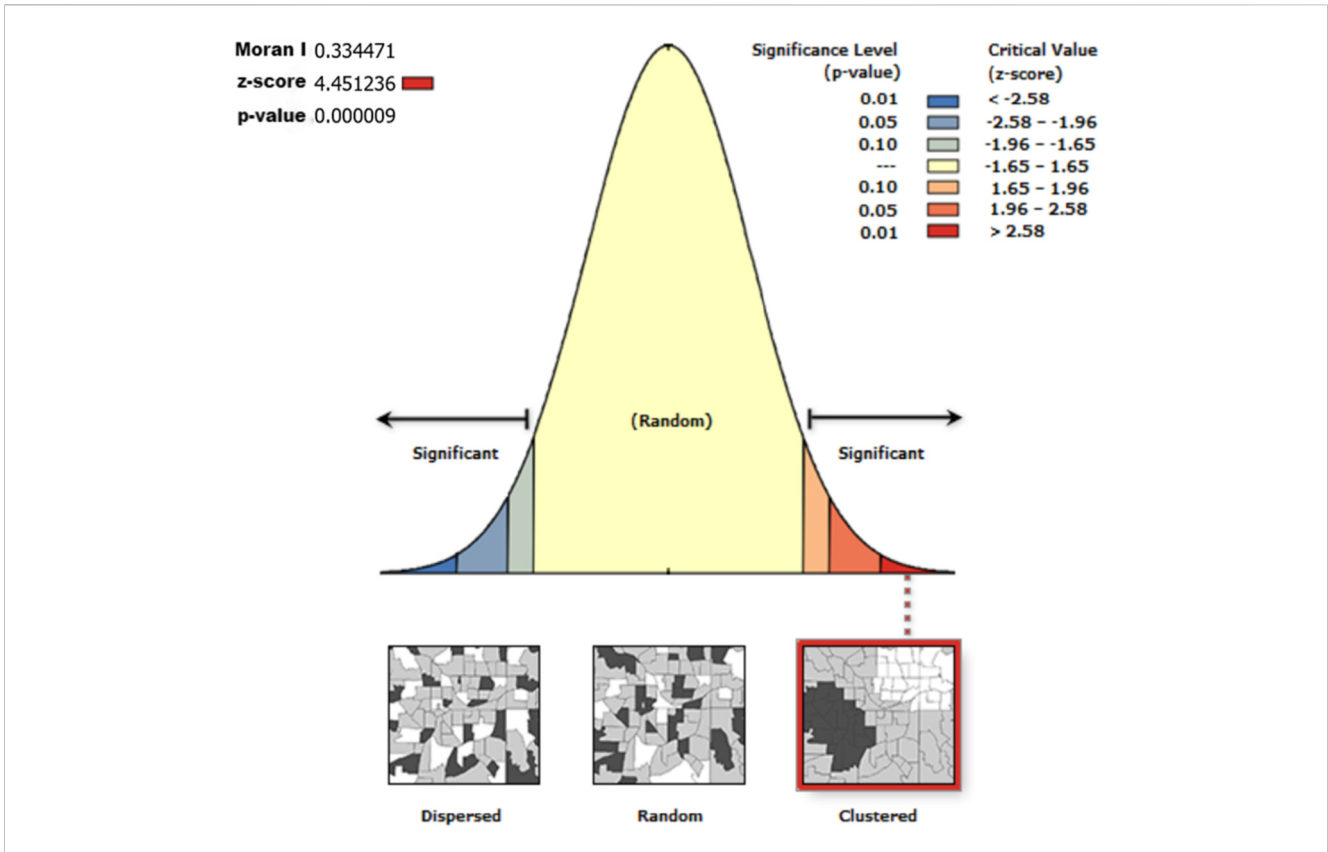


FIGURE 5 2023 Moran's I report of ecological civilization construction index.

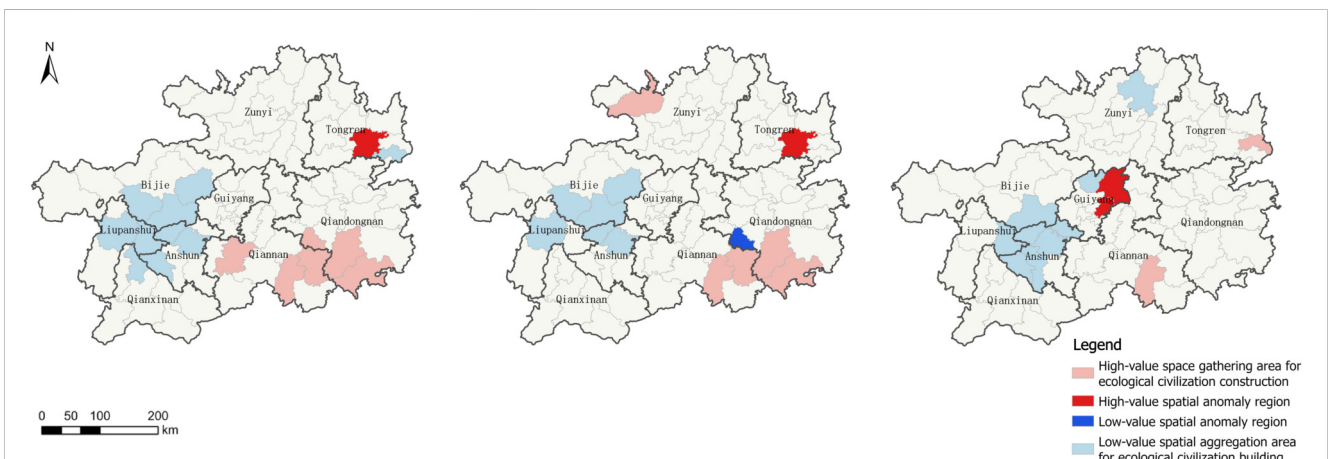


FIGURE 6 Local Anselin local Moran's I clustering and outlier analysis (2012–2023).

counties with high or low ecological civilization construction level indexes tend to be adjacent, which is consistent with the actual situation.

3.3.2 Local spatial autocorrelation analysis

The global Moran's I index obtained from the global spatial autocorrelation analysis indicates the spatial correlation of the

ecological civilization construction level of 88 districts/counties during the study period as a whole, but it cannot explain the spatial correlation in local areas. To further test the spatial effect relationship between districts/counties, it is necessary to conduct local spatial autocorrelation testing. The Anselin Local Moran's I statistic was used to identify statistically significant hotspots, coldspots, and spatial outliers, which can more intuitively

visualize the specific effects of local spatial correlation between districts/counties. The results are shown in [Figure 6](#).

From 2012 to 2023, the global Moran's I index of the county-level ecological civilization construction level in Guizhou Province increased from 0.2067 to 0.3345, and the degree of spatial correlation continued to strengthen, showing the characteristics of "slowing down of low-value agglomeration and strengthening of high-value agglomeration". In 2023, high-value agglomeration areas were formed in counties such as Huishui, Dushan, and Leishan in the southeast, and low-value agglomeration areas were in counties such as Shuicheng and Nayong in the west. This spatial correlation is stable (small variance and low variation of Moran's I index), which is due to the increase in regional exchanges and cooperation and the promotion of policy coordination.

This characteristic provides a basis for strategy formulation: relying on high-value areas to build an "ecological demonstration belt" to promote successful models; implementing "one county, one policy" precise support for low-value areas; establishing a "high-value area + low-value area" pairing mechanism to promote coordinated development; and promoting the province's improvement from "local agglomeration" to "global balance".

4 Improvement paths for the ecological civilization construction level in Guizhou Province

4.1 Spatial heterogeneity of environmental governance performance under karst geomorphological constraints

Results indicate that environmental governance performance in Anshun, Southeast Guizhou, and Tongren lags behind the provincial average, revealing a spatial non-equilibrium in Guizhou's ecological civilization construction. This spatial heterogeneity is representative of international karst regions. For instance, during periods of accelerated urbanization, both the Mediterranean Basin and the Southeast Asian karst belt faced surging pollution control costs due to the complex binary surface-subsurface spatial structure ([Bakalowicz, 2018](#); [Li Vigni et al., 2023](#)). From a causal mechanism perspective, this governance deficit is not merely a technical lack but reflects the diminishing marginal utility of local fiscal capacity under extreme geomorphological conditions. The complexity of anti-seepage and pipe network construction in karst terrains makes the per-unit cost of environmental infrastructure significantly higher than in plain regions. Consequently, fiscally weak regions are prone to a structural dilemma in public goods supply when balancing "economic growth priority" with "high-cost environmental investment" ([Saha et al., 2022](#)). Therefore, to break the lock-in effect of habitat constraints, it is imperative to establish a provincial-scale fiscal coordination and distribution mechanism for environmental governance.

4.2 Structural path dependency and carbon lock-in effects in resource-based regions

The lagging low-carbon transition in heavy industrial bases such as Liupanshui and Southwest Guizhou reflects the

profound inertia of resource-dependent regions in pursuing "Dual Carbon" goals ([Fan et al., 2022](#)). This process closely mirrors the transition trajectory of the Andean mining belt ([Bedoya Londoño et al., 2024](#)). In that region, the global energy transition's reliance on strategic minerals (metallic minerals) has compelled traditional mining to act as a low-carbon energy supplier, while simultaneously exacerbating environmental burdens, community conflicts, and sustainability challenges. This underscores the significant lag and inertia characteristic of resource-dependent regions during low-carbon shifts. In this study, such resistance is attributed to a multidimensional "carbon lock-in effect." The coal transition involves not only the lock-in of physical capital but also the institutional dependency of local governments on established fiscal and taxation pathways ([Diluiso et al., 2021](#)). This path dependency prevents low-carbon technologies from penetrating entrenched interest structures. Overcoming this challenge requires provincial-level interventions through green financial incentives and rigid constraints to forcibly break the resource-intensive growth loop.

4.3 Evolution of collaborative governance paradigms from a regional ecological coupling perspective

The spatial clustering pattern of "High in the Southeast and Low in the West" is essentially the product of a long-term spatial mismatch between natural resource endowments and historical industrial layouts. From an international perspective, the Alpine region has strengthened horizontal collaborative governance between ecological security zones and economic beneficiary zones through trans-regional cooperation ([Bornemann et al., 2024](#)). Analyzing the collaborative mechanism, the "high-value ecological zones" in southeastern Guizhou bear substantial development opportunity costs to maintain biodiversity. This functional imbalance necessitates a transition in governance paradigms from administrative-based management to an "eco-premium compensation paradigm." Research on China's Gross Ecosystem Product (GEP) accounting emphasizes that establishing a trans-regional horizontal compensation mechanism is key to mitigating spatial inequality ([Yan et al., 2024](#)). By refining GEP accounting and promoting the spatial reconfiguration of green resource interests, a balanced development of ecological civilization across the province can be achieved.

4.4 Spatio-temporal deviation of ecological culture and value reconstruction under rapid urbanization

The study reveals that ecological culture construction generally lags behind hard engineering indicators of environmental governance, reflecting a decoupling of spiritual civilization from institutional frameworks. The primary driving mechanism is the suppression of non-material value systems by "materialism-oriented" rapid urbanization. According to the IPBES (2022) Global Values Assessment Report, in the pursuit of visible governance performance, attention and resources are often prioritized for physical engineering,

leading to an “institutional vacuum” in the cultivation of cultural soft power (Vatn et al., 2024). As populations migrate to cities on a large scale, the “reverence for nature” inherent in traditional cultures is gradually weakened or even severed under the impact of modern consumerism and materialistic lifestyles. Empirical studies demonstrate that urbanization not only alters lifestyles and behavioral patterns but also leads to the loss of traditional ecological knowledge (TEK), including local plant knowledge and experiential environmental wisdom, which are vital carriers of cultural value (Arjona-García et al., 2021; Rangel et al., 2024). Guizhou should tap into the ecological genes within its ethnic cultures, transforming ecological culture demonstration bases into educational platforms with local identity to reconstruct ecological ethics within the urbanization process.

4.5 Adaptive paths and resilience enhancement in ecological civilization governance systems

The core of perfecting the basic institutional framework for ecological civilization lies in constructing a closed-loop mechanism with self-rectification capabilities. Drawing on the international frontier theory of “adaptive governance,” a governance system must be acutely sensitive to fluctuations in complex ecosystems and respond accordingly (Folke et al., 2005). Transformative governance requires institutional resilience to manage uncertainty. By establishing a feedback system based on remote sensing big data and dynamic accounting (Wang et al., 2025), counties in Guizhou can dynamically adjust development thresholds based on real-time changes in environmental carrying capacity. Under the institutional framework of Chinese-style modernization, the essence of realizing the value of ecological products is the capitalization of ecological assets. By clarifying ecological property rights and refining differentiated evaluation mechanisms, the political mandate of “holding the two bottom lines” (development and ecology) can be internalized as an endogenous driver for regional development.

5 Conclusion

This study constructed a multidimensional evaluation system integrating ecological security, economic, cultural, and institutional dimensions to systematically measure the ecological civilization construction levels in Guizhou Province for 2012, 2018, and 2023. Through a dual spatio-temporal analysis, the research revealed the evolutionary logic of typical karst regions in Southwest China during the modernization process. The main conclusions are as follows:

1. The evolution of ecological civilization exhibits significant “non-equilibrium growth,” where the coupling of karst habitat constraints and institutional efficacy determines regional performance.

The measurement results indicate that while the overall ecological civilization level in Guizhou Province improved significantly from 2012 to 2023, marked spatial heterogeneity persisted, forming a pattern

of “leading growth in the southeast and lagging catch-up in the west.” Causal mechanism analysis suggests that this imbalance stems from the impact of karst habitat constraints on governance costs and the disparities in fiscal capacity to support environmental investment. Dimensional analysis shows that while ecological security and institutional dimensions have made substantial progress, ecological culture remains a bottleneck. These findings suggest that ecological transition in karst regions must transcend “one-size-fits-all” approaches in favor of spatially differentiated, precision governance strategies that address regional weaknesses while leveraging local ecological advantages.

2. The intensifying spatial autocorrelation induces regional “clustering” effects, providing scientific support for the construction of trans-regional collaborative governance systems in karst areas.

The Global Moran’s I index rose steadily from 0.2067 in 2012 to 0.3345 in 2023, reflecting an increasing geospatial dependence among counties in their ecological civilization construction levels. The spatial evolution pathways indicate an accelerating reconfiguration of high-value and low-value clusters, generating significant spatial spillover effects. This pattern underscores the urgency and feasibility of regional joint governance: by leveraging the demonstrative role of “High-High” (H-H) clusters in the southeast, cross-regional resource allocation and technical assistance can effectively drive ecological restoration and green transition in the low-value western regions. This conclusion provides a strategic basis for narrowing developmental gaps within karst regions and enhancing overall regional governance efficiency.

3. The “Evaluation-Mechanism-Path” framework developed in this study possesses international applicability, providing a “China Solution” for the green modernization of karst habitats and ecologically fragile regions globally.

This study identifies critical barriers such as the “carbon lock-in effect” in resource-based city transitions and the “cultural rupture” in ecological cognition. By analyzing the typical case of Guizhou, this research paradigm demonstrates the possibility of harmonizing ecological integrity with socio-economic development. The findings offer a replicable analytical framework for the sustainable development of similar ecologically fragile regions worldwide and contribute significantly to the global discourse on ecological civilization systems.

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

QY: Writing – original draft, Conceptualization, Writing – review and editing, Methodology. LZ:

Writing – original draft, Data curation, Visualization. GY: Funding acquisition, Writing – review and editing. QC: Data curation, Writing – original draft.

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