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Climate-environment resiliency and adaptation

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Climate-environment resiliency and adaptation

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Editorial: Climate-environment resiliency and adaptation

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Editorial on the Research Topic
Climate-environment resiliency and adaptation

1 Introduction

The accelerating pace of global climate change has triggered a cascade of environmental and societal impacts—from intensified storms, droughts, and heatwaves to rising seas, ecosystem degradation, and infrastructure failures. These impacts not only threaten ecosystems but also disrupt economies, exacerbate social inequalities, and compromise public health and social stability. As these challenges grow in complexity and interconnectedness, resilience—the capacity of systems to anticipate, absorb, recover from, and adapt to disturbances—has become a critical guiding principle for science, policy, and practice.

Despite substantial progress, resilience and adaptation research still face key barriers. Many studies remain siloed within specific disciplines or scales, limiting the ability to translate scientific insights into actionable strategies. Others rely heavily on correlative approaches, without sufficiently capturing underlying processes or feedback between human and natural systems. This Research Topic seeks to bridge these gaps by bringing together a diverse set of studies that address resilience from complementary perspectives—integrating physical science, social science, data analytics, policy, and engineering.

The 14 papers in this Research Topic provide a rich cross-section of current research efforts. They range from biophysical process modeling and ecosystem responses to adaptation policy analysis and social vulnerability assessment. Together, they reflect a growing consensus: addressing the challenges of a changing climate requires a systemic, multi-scale, and interdisciplinary approach.

2 Overview of the papers in this Research Topic

Several contributions focus on how societies perceive and respond to climate impacts, highlighting the importance of traditional knowledge, socioeconomic context, user-inspired projects and initiatives, and adaptive capacity. Ayompe and Epie explore Africa's climate

vulnerabilities, emphasizing the role of indigenous knowledge systems, climate-smart agriculture, and local initiatives in strengthening resilience. Their work demonstrates how bottom-up approaches can complement scientific modeling and policy interventions by case studies from the Sahel and sub-Saharan Africa. These examples reveal how localized adaptation—ranging from early warning systems to governance reform—enhances regional resilience. Chen et al. revisit traditional Chinese agrometeorological proverbs, validating their scientific relevance and demonstrating their potential to support climate-informed agricultural decision-making. Begum et al. examine gendered perceptions and adaptive behaviors among nut farmers in Bangladesh, showing that factors such as education, farming experience, and income diversification may influence adaptive capacity.

Understanding how natural systems respond to climate variability is essential for developing effective adaptation strategies. Several papers in this Research Topic make significant contributions to this area. Pang et al. analyze spatiotemporal patterns of soil heat flux in northern China, providing new insights into soil-vegetation-atmosphere energy exchanges under changing climatic conditions. Huang et al. examine how rapid urbanization and extreme weather influence wet-bulb temperature dynamics in Guangdong Province, highlighting implications for thermal risk and urban planning. Harjupa and Nakakita study winter monsoon-driven warm rain processes in the Java Sea, demonstrating how atmospheric circulation patterns contribute to extreme precipitation and flood hazards. Zhang and Wu examine how climate change, vegetation cover, and land-use patterns jointly regulate water and carbon use efficiency in China's river basins—insights that are crucial for ecosystem management and carbon mitigation strategies.

Several papers address the challenges of protecting critical infrastructure and communities from climate-related hazards through risk assessment, modeling, and adaptation planning. Kamara et al. propose a cost-effective, five-phase framework for assessing climate risks to unpaved road networks in Sierra Leone. Their approach offers a practical model for infrastructure resilience in resource-constrained settings. Ma et al. develop an integrated urban flood risk assessment methodology combining hydrodynamic modeling with fuzzy matter-element theory, demonstrating its applicability in the Chinese city of Zhengzhou. Their findings resonate with broader themes throughout this Research Topic, emphasizing resilience planning, integrated data management, and the coupling of hazard modeling with socioeconomic assessment. Helgeson et al. explore co-benefits in climate resilience planning, advocating for integrated approaches that simultaneously address environmental, health, and social outcomes.

Climate change is not only a physical problem but also a deeply social one, affecting migration patterns, governance structures, and policy frameworks. Aziz et al. conduct a comprehensive bibliometric analysis of climate-induced migration in the Global South. Their findings reveal evolving research priorities, as well as gaps related to justice, representation, and policy engagement. Hamer et al. assess adaptation strategies across diverse agroecological zones, highlighting the importance of stakeholder participation, local leadership, coherent policy design, and the integration of traditional knowledge with modern technologies.

The development of new decision-support tools and methodologies is critical to translating resilience research into actionable strategies. Katende presents a scalable framework combining econometric modeling and geospatial interpolation for assessing climate resilience in data-scarce regions. This approach enhances the capacity of policymakers to make informed decisions even with limited data availability.

3 Conclusion and future directions

The papers in this Research Topic reflect the remarkable breadth and depth of current research on climate resilience and adaptation. Collectively, they highlight several key messages that are shaping the future of this field:

- Interdisciplinarity is essential. Building resilience requires integrating insights from hydrology, ecology, social science, engineering, and policy.
- Local context matters. Solutions must be tailored to socioeconomic, cultural, and ecological conditions while remaining scalable and transferable.
- Data and technology are enabling transformation. Advances in modeling, remote sensing, and machine learning are expanding our capacity to understand, predict, and respond to climate impacts.
- Social considerations should remain an important focus. Effective adaptation strategies should account for differing community needs, support those most at risk, and draw on a broad range of knowledge and experience.
- Bridging science and policy is critical. Research must inform decision-making at all levels—from local governance to global frameworks—to ensure that adaptation measures are both scientifically sound and practically viable.

As climatic pressures continue to intensify and their cascading impacts on natural and human systems become increasingly evident, the imperative for collaborative cross-disciplinary approaches is more pronounced than ever. We hope this Research Topic not only captures the state of current scientific understanding but also serves as a catalyst for advancing future research that effectively bridges science and practice, integrates knowledge into policy frameworks, and translates innovation into tangible societal benefits. By uniting diverse perspectives, methodologies, and domains of expertise, the contributions presented here collectively point toward a more resilient and sustainable future for communities and ecosystems worldwide.

Author contributions

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Factors influencing carbon and water use efficiency in changing environments

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Introduction: Vegetation plays a crucial role in terrestrial ecosystems, acting as a vital link connecting the lithosphere, hydrosphere, and atmosphere in terms of energy flow and material cycling. Changes in surface vegetation significantly regulate the water cycle, energy flow within terrestrial surfaces, and global carbon balance.

Methods: This study focuses on nine major river basins in China to quantitatively investigate the impacts of climate factors, vegetation dynamics, and land use changes on carbon use efficiency (CUE) and water use efficiency (WUE).

Results: The primary controlling factors of WUE trends are NDVI (average contribution: 33.75% ± 6.90%) and VPD (average contribution: 28.04% ± 3.98%). NDVI predominates in the Haihe, Yellow River, Yangtze River, Pearl River, and Songliao River basins, while shortwave radiation (Srad) dominates in the southeastern rivers and inland river areas, and humidity (Shum) in the southwestern river basins. For CUE trends, the main controlling factors are Srad (average contribution: 36.46% ± 3.40%) and precipitation (Pre) (average contribution: 26.72% ± 5.20%). NDVI negatively influences the Huaihe River and southeastern river basins, while Pre negatively influences the Songliao River and Yellow River basins, and Srad negatively influences the Huaihe and southwestern river basins. Pre predominates in the Huaihe, Songliao, Haihe, southwestern river basins, and inland river areas, while Srad predominates in the Pearl River, Yangtze River, and Yellow River basins.

Discussion: Climate factors and vegetation dynamics have significant regional impacts on WUE and CUE across different river basins, especially the roles of NDVI and VPD on WUE, and Srad and precipitation on CUE. These differences underscore the importance of developing region-specific management strategies to optimize ecosystem services in each basin.

KEYWORDS

water use efficiency, carbon use efficiency, land use, vegetation dynamics, China

1 Introduction

Vegetation plays a crucial role in terrestrial ecosystems, serving as a key intermediary in the exchange of energy and matter between the lithosphere, hydrosphere, and atmosphere. Changes in vegetation have significant regulatory effects on the hydrological cycle, energy transfer within terrestrial surfaces, and the global carbon cycle (Foley et al., 1996; Ostle et al., 2009). Faced with the dual impacts of climate change and human activities, dynamic changes in vegetation not only respond to external environmental changes but also serve as

explicit indicators of the internal state of ecosystems. Therefore, vegetation is considered an important indicator for assessing ecosystem health and sensitivity to environmental changes (Qi et al., 2019; Seddon et al., 2016). The characteristics of vegetation changes are of significant importance for the overall adaptability and stability of ecosystems. On the other hand, vegetation is not merely a passive recipient of external environmental changes; it dynamically responds to the external environment through its biophysical and biochemical processes. In this process, vegetation exerts significant influences on regional and global carbon-water cycling systems through ecological and physiological processes such as photosynthesis and transpiration (Hu et al., 2008).

Carbon Use Efficiency (CUE) determines the rate at which energy and matter flow towards higher trophic levels, converting plant produced carbon into microbial products and ecosystem carbon storage. It is typically expressed as the ratio of Net Primary Productivity (NPP) to Gross Primary Productivity (GPP) (Lu et al., 2011; DeLucia et al., 2007). Water Use Efficiency (WUE) in vegetation, defined as the amount of fixed carbon per unit of water transpired, quantifies the trade-off between carbon gain and water loss in terrestrial ecosystems. This efficiency is commonly represented by the ratio of ecosystem biomass production (GPP or NPP) to Evapotranspiration (ET) (Sinsabaugh et al., 2013). A thorough understanding of the dynamic changes and controlling factors of CUE and WUE is crucial for predicting ecosystem responses to climate change. CUE and WUE serve as vital indicators of carbon and water cycling in vegetation ecosystems, reflecting vegetation growth status and environmental responsiveness. By calculating and analyzing these indicators, we can compare differences in carbon and water cycling among different ecosystems and understand how plants respond to environmental changes (Fisher et al., 2017).

Historically, studies of WUE have focused on individual plants, with gas exchange methods offering insight at the leaf level. With advancements in remote sensing, large-scale assessments of WUE have become possible, expanding research to ecosystems such as forests, grasslands, and farmlands (John et al., 2013). Remote sensing data, especially from satellites, now enables regional and global-scale analysis of water use efficiency, though results can vary based on factors like vegetation type, leaf area index (LAI), radiation, temperature, and precipitation (Xu et al., 2019). Despite these advancements, challenges remain in understanding how these factors influence WUE across spatial and temporal scales.

Land Use and Cover Change (LUCC) plays a significant role in altering terrestrial carbon and water cycles by changing surface energy balances, water availability, and nutrient flows (Liu et al., 2023; Posch and Bennett, 2009). Studies across various regions highlight the temporal and spatial variability of WUE. For instance, in the Amazon Basin, researchers have observed distinct spatial patterns of WUE that differ from those in East Asia or the United States (Zhou et al., 2018). Zhao et al. (2020) found that WUE in southwest China varies across vegetation types, ranking from highest to lowest as forest, shrubland, farmland, and grassland. This finding contrasts with results from the Loess Plateau, where Zhang et al. (2016) ranked WUE from highest to lowest as grassland, woodland, shrubland, and farmland. Such comparisons underscore the need to understand how regional factors, such as climate and land use, influence WUE and carbon-water interactions.

Regarding CUE, past studies often treated CUE as a fixed value (~0.5), assuming that about half of the carbon assimilated is allocated to biomass (Zhang et al., 2014). However, recent findings challenge this assumption. For instance, (Campioli et al., 2015) showed that CUE varies depending on environmental conditions and vegetation types, while DeLucia et al. (2007) argued that CUE should be considered an ecosystem specific parameter. Remote sensing data from the Moderate Resolution Imaging Spectroradiometer (MODIS) revealed significant spatial variability in CUE, influenced by geographic and climatic factors (Chen et al., 2018; Zhang et al., 2019). This variability aligns with global observations that suggest CUE fluctuates with climate, ecosystem type, and human management practices.

While many studies have focused on large-scale assessments of CUE and WUE, uncertainties remain. For example, models estimating CUE vary in how they parameterize photosynthesis and autotrophic respiration, contributing to inconsistent results (Chen et al., 2018; Waring et al., 1998). Moreover, research from regions such as the Amazon Basin, East Asia, and the Loess Plateau presents differing conclusions on the drivers of CUE and WUE, highlighting the importance of geographical context.

This study aims to investigate the dynamic relationships among climatic factors, vegetation dynamics, and land use types with carbon-water use efficiency, determining the contributions of climatic factors and vegetation dynamics to changes in carbon-water use efficiency. The findings contribute to assessing the health of ecosystems in different watersheds. Based on the characteristics of different watersheds and their primary influencing factors, targeted resource management strategies can be implemented to enhance water resource utilization efficiency and carbon cycle stability.

2 Materials and methods

2.1 Study area

China is located in the northern part of the Eastern Hemisphere, spanning latitudes between 3.86°N and 53.55°N and between 73.66°E and 135.05°E, and is on the eastern part of the Eurasian continent and the western part of the Pacific Ocean. The terrain is higher in the west and lower in the east, with mountains, plateaus and hills dominating the terrain, accounting for about 67% of the land area, while basins and flat principles account for about 33% of the land area. Its mountain ranges are mainly distributed along the east-west-northeast-southwest direction, including the Karakorum Mountains, Yinshan Mountains, Qinling Mountains, Changbai Mountains, Daxing'anling Mountains, Taiwan Mountains and Hengduan Mountains. China's climate is characterized by high temperatures and rainy summers, cold winters with little rain, and a high degree of consistency between the high temperature period and the rainy period, which is a clear manifestation of the universal law of monsoon climate. Geographically, China is located in the world's largest continent the eastern part of Asia and Europe, and at the same time adjacent to the world's largest ocean the west coast of the Pacific Ocean, and its southwest and the Indian Ocean is not far away. This unique geographic location determines that

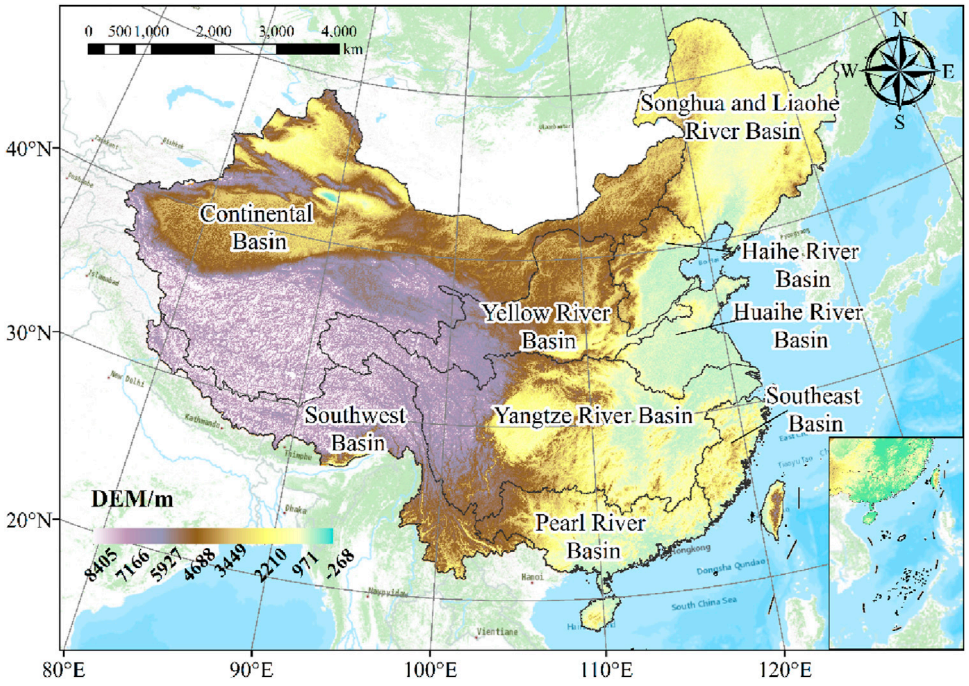


FIGURE 1
Study area.

TABLE 1 Basic table of the nine major river basins in China.

River basin name	Area (km^2)	Primary vegetation	Climate
Continental Basin, CtB	3,338,945	Grassland, Desert	Plateau mountain climate, Temperate continental climate
Southwest Basin, SWB	852,634	Forest, Grassland	Subtropical monsoon climate, Plateau mountain climate
Yellow River Basin, YeRB	808,905	Farmland, Forest	Temperate monsoon climate, Temperate continental climate
Haihe River Basin, HRB	316,992	Farmland, Forest	Temperate monsoon climate, Temperate continental climate
Songhua and Liaohe River Basin, SLRB	1,238,125	Farmland, Forest	Temperate monsoon climate
Huaihe River Basin, HuRB	323,950	Farmland	Temperate monsoon climate
Southeast Basin, SEB	240,319	Farmland, Forest	Subtropical monsoon climate
Yangtze River Basin, YRB	1,799,222	Farmland, Forest	Subtropical monsoon climate
Pearl River Basin, PRB	570,561	Forest	Subtropical monsoon climate

China's climate is strongly influenced by both the continent and the ocean, which makes the monsoon climate characteristics particularly prominent. These climatic characteristics not only affect China's natural environment, but also have a profound impact on agricultural production, water resource distribution, and human settlement patterns (Figure 1; Table 1).

2.2 Data acquisition and processing

2.2.1 ET data

The evapotranspiration data are derived from an actual evapotranspiration dataset, known as the Terrestrial Evapotranspiration Data for China (TEDAC), based on the Nonlinear Complementary Relationship (CR) model. TEDAC operates at a spatial resolution of 0.1° and a temporal resolution at monthly scale. The dataset spans from January 2000 to December 2017, encompassing Actual Evapotranspiration (AET). Validation of TEDAC AET dataset was conducted using *in situ* measurements from 13 eddy covariance stations, achieving Nash Sutcliffe efficiency values ranging from 0.72 to 0.94 (https://doi.org/10.11888/AtmosPhys.tpe.249493.file).

2.2.2 Vegetation data

MODIS/Terra NPP product originates from the MOD17A3HGF v006 dataset provided by NASA for the years

TABLE 2 Data source.

Data	Spatial resolution	Temporal resolution	Data source
Evapotranspiration, ET	0.1°	Year	https://data.tpdc.ac.cn/
Net Primary Productivity, NPP	500 m		https://lpdaac.usgs.gov/
Gross Primary Production, GPP	500 m		https://lpdaac.usgs.gov/
Land use	30 m		https://zenodo.org/
Temperature, Temp			
Precipitation, Pre			
Downward shortwave radiation, Srad	0.1°		https//www.tpdc.ac.cn/
Specific humidity, Shum	0.1°		https//www.tpdc.ac.cn/
Wind Speed, WS			
Vapor Pressure Deficit, VPD	0.1°		http://data.cma.cn/
Leaf Area Index, LAI	500 m	Year	https://lpdaac.usgs.gov/
Normalized Difference Vegetation Index, NDVI	1 km		https://www.resdc.cn/
Standardized Precipitation Evapotranspiration Index, SPEI	1 km		https://www.scidb.cn/

Note: The resolutions of the aforementioned datasets vary. We standardized the resolution of these datasets to 1 km × 1 km using resampling methods.

2000–2017 (https://lpdaac.usgs.gov/), with a spatial resolution of 1 km × 1 km. Data processing involved using the Modis Reprojection Tool (MRT) software for calculations.

Gross Primary Productivity (GPP) product is sourced from the MOD17A2H dataset provided by NASA for the years 2000–2017 (https://lpdaac.usgs.gov/). This dataset features an 8-day composite with a spatial resolution of 500 m, based on the concept of radiation use efficiency, making it potentially valuable as input data for models.

2.2.3 Land use data

The CLCD dataset with 30 m resolution offers higher spatial resolution and a longer historical record compared to existing annual land cover products such as MCD12Q1 and ESACCILC. Third party validation of the CLCD dataset demonstrates overall accuracy surpassing MCD12Q1, ESACCILC, FROM_GLC (Global Land Cover Fine Resolution Observation and Monitoring), and GlobaLand30.

2.2.4 Other data

Meteorological data including Temperature (Temp), Precipitation (Pre), Downward Shortwave Radiation (Srad), Specific Humidity (Shum), and Wind Speed (WS) are sourced from the China Meteorological Forcing Dataset (CMFD) (https://data.tpdc.ac.cn/). CMFD provides national meteorological data from 1979 to 2018 at a spatial resolution of 0.1° and a temporal resolution of 3 h, widely used for model driving and data analysis research. For each station, flux data on rainy days and the following day, as well as outliers, were excluded. Monthly mean temperature values (Ta) and cumulative monthly precipitation (P) are derived from daily data. Additionally, Vapor Pressure Deficit (VPD) is calculated using relative humidity (RH, %) and Ta (°C) according to the formula provided (http://data.cma.cn/) (Equation 1).

$$VPD = 0.61078 \times e^{\frac{17.27 \times Ta}{Ta+237.3}} \times (1 - RH) \quad (1)$$

Leaf Area Index (LAI) data are obtained from LP DAAC (https://lpdaac.usgs.gov/); Normalized Difference Vegetation Index (NDVI) data are sourced from the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (https://www.resdc.cn/). Data for the Standardized Precipitation Evapotranspiration Index (SPEI) are acquired from the Scientific Data Bank (https://www.scidb.cn/).

While these datasets provide comprehensive coverage and high spatial resolution, they are subject to inherent limitations (Table 2). For instance, remote sensing products like MODIS may be affected by cloud cover, atmospheric conditions, and sensor calibration issues, potentially influencing the accuracy of derived metrics such as NPP and GPP. Additionally, while the CLCD dataset offers improved spatial accuracy, challenges may arise in interpreting land use changes over time due to classification errors or changes in land management practices.

2.3 Research method

2.3.1 Calculation method of carbon-water use efficiency

WUE (gC/m^2·mm) can be expressed as the ratio of NPP (gC/m^2) to ET (mm) (Equation 2):

$$WUE = \frac{NPP}{ET} \quad (2)$$

CUE can be expressed as the ratio of NPP (gC/m^2) to GPP (gC/m^2) (Equation 3).

$$CUE = \frac{NPP}{GPP} \quad (3)$$

These calculations allow for the assessment of carbon sequestration relative to water usage, providing insights into ecosystem efficiency in terms of resource utilization.

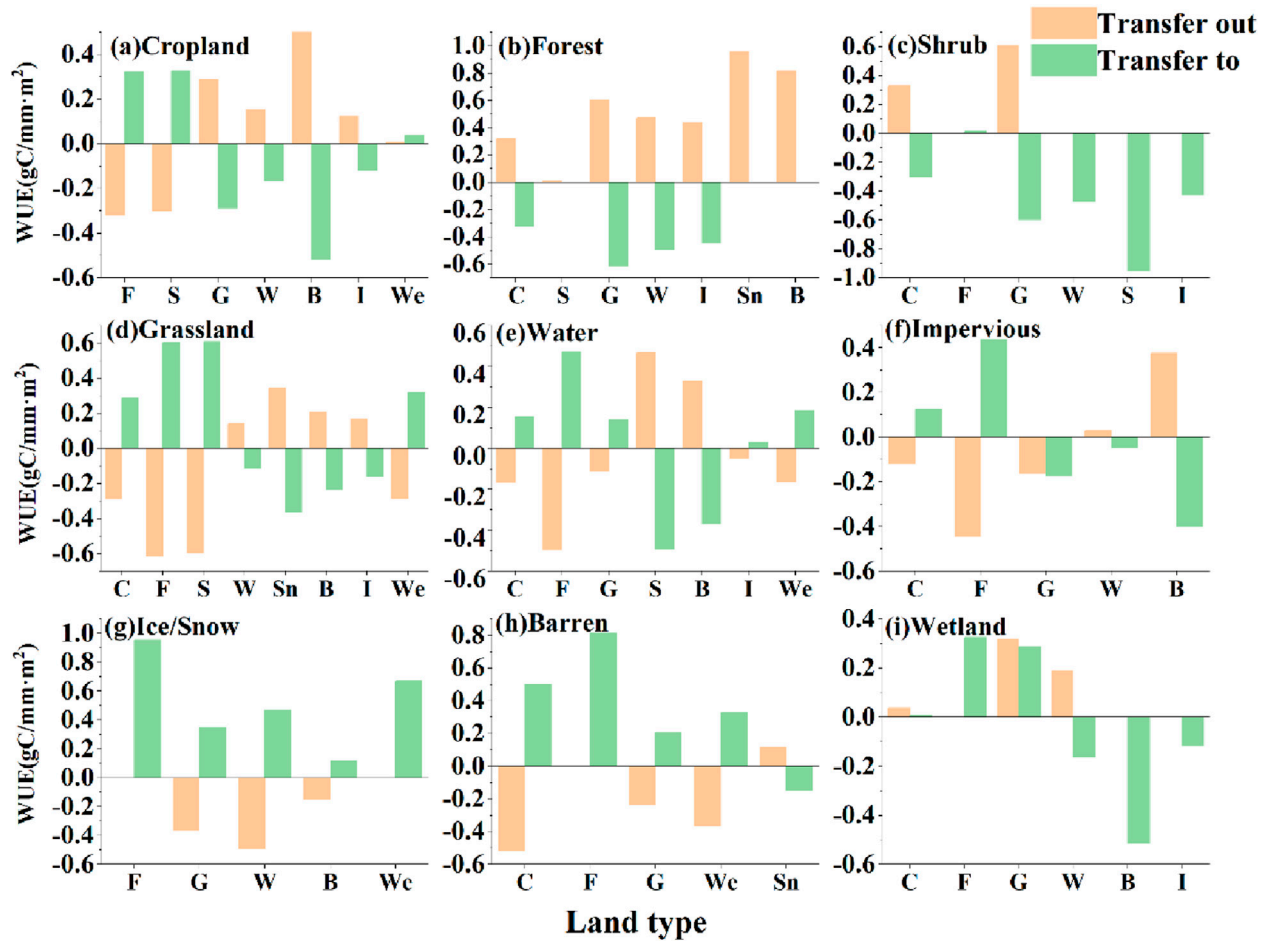


FIGURE 2
Changes in WUE caused by land cover type conversions from 2000 to 2017 (C: Cropland; F: Forestland; S: Shrubland; G: Grassland; W: Water bodies; Sn: Ice/Snow; B: Bare land; I: Impervious surfaces; We: Wetland. "Transition to" refers to WUE changes when other land cover types are converted to land cover type j; "Transition from" refers to WUE changes when land cover type j is converted to other land cover types). **(A)** Cropland; **(B)** Forest; **(C)** Shrub; **(D)** Grassland; **(E)** Water; **(F)** Impervious; **(G)** Ice/Snow; **(H)** Barren; **(I)** Wetland.

2.4 Relative contribution rate

To analyze trends in WUE, climate factors, and vegetation factors, we employed a simple linear regression model to determine the slope, which indicates the direction and strength of the relationship over time. This approach provides a straightforward method for quantifying changes in WUE and its association with climatic variables. To minimize the influence of non-climatic factors on WUE, we utilized the first difference detrending method. This technique removes trends from the data, allowing for a clearer examination of the relationships between climate variables and WUE. Detrending is crucial in time series analysis as it helps isolate the effect of short-term fluctuations from long-term trends. Given the inter correlation among climate factors, we conducted partial correlation analysis to quantify the relationship between the detrended climate factors and detrended WUE. This method controls for the effects of other variables, allowing us to focus on the direct relationship between the two primary variables of interest. By identifying the factor with the highest partial correlation coefficient, we determined the dominant climate factor affecting WUE.

To further quantify the contribution of climatic factors to WUE, we performed multiple linear regression analysis. In this analysis, the first differences of the climate factors served as predictor variables, while the first difference of WUE was treated as the response variable (Chen et al., 2017) (Equation 4):

$$Y_{\mathrm{ds}} = \mathrm{a}_1 X_{1ds} + \mathrm{a}_2 X_{2ds} + \mathrm{a}_3 X_{3ds} + \cdots\cdots \mathrm{a}_n X_{nds} \quad (4)$$

where, Y_{ds} represents the normalized detrended WUE; a_i denotes the regression coefficients for each predictor variable; X_{ids} refers to the normalized detrended climate factors. This method allows us to quantify how changes in climate factors contribute to variations in WUE, providing a clearer understanding of the interplay between climatic and anthropogenic influences.

Assuming that the dependent variable responds similarly to both climatic trends and interannual climatic variations, the contribution of climate to the WUE trend from 2000 to 2017 can be quantified using the aforementioned regression coefficients and the trends of the climate factors (Equations 5, 6).

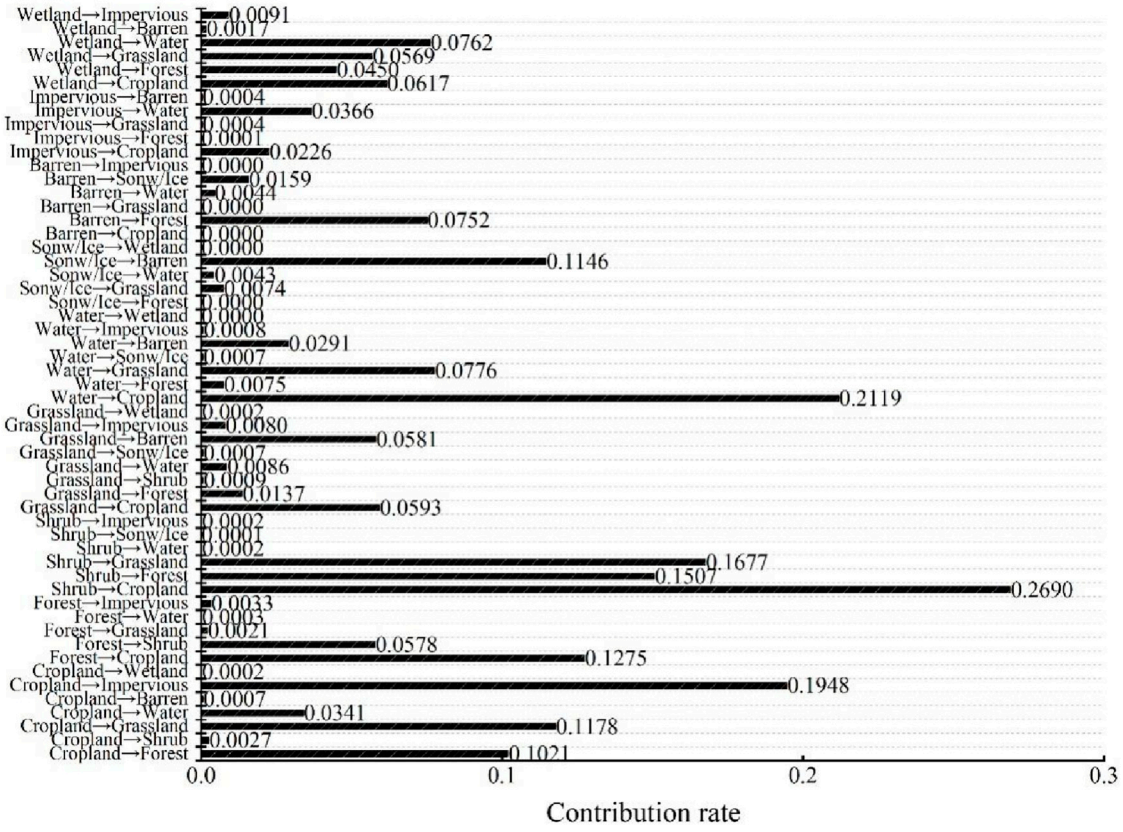


FIGURE 3
Contribution of land use change to changes in Water Use Efficiency (WUE).

$$Q_c = \sum_{i=1}^{n} a_i X_{is_trend} \quad (5)$$

$$Q_{ac} = \frac{Q_c}{Y_{s_trend}} * Y_{trend} \quad (6)$$

where, X_{is_trend} represents the trend of the normalized climate factors; Q_c denotes the contribution of climate to the trend of normalized WUE; Y_{s_trend} refers to the trend of normalized WUE; Y_{trend} indicates the overall trend of WUE; Q_{ac} represents the actual contribution of climate to the WUE trend. This comprehensive analysis enables a nuanced understanding of the climatic influences on WUE trends over the specified period.

3 Results

3.1 Impact of land use conversion on carbon-water use efficiency

3.1.1 Impact of land use conversion on water use efficiency

The average WUE values for the nine land cover types in this study are ranked as follows: forest (1.134 gC/mm·m^2) > shrubland (1.109 gC/mm·m^2) > wetland (0.848 gC/mm·m^2) > cropland (0.818 gC/mm·m^2) > impervious surfaces (0.688 gC/mm·m^2) > water bodies (0.630 gC/mm·m^2) > grassland (0.522 gC/mm·m^2) > bare land (0.292 gC/mm·m^2) > ice/snow (0.169 gC/mm·m^2).

Woodlands and shrubs demonstrate the highest WUE. Their conversion to other land types results in decreased WUE, with the most significant declines observed when woodlands are converted. Conversely, mutual conversions between shrubs and woodlands positively influence WUE, though the changes are greater when woodlands convert to shrubs. Vegetation degradation has a larger impact on WUE than vegetation restoration (Figure 2).

Between 2000 and 2017, shrubland to cropland conversion decreased WUE by 0.30 gC/mm·m^2 (26.90% contribution), while cropland to forestland increased WUE by 0.32 gC/mm·m^2 (10.21%). Other significant changes include cropland to impervious surfaces (decrease of 0.12 gC/mm·m^2, 19.48% contribution) and grassland to cropland (increase of 0.287 gC/mm·m^2, 5.93%). Overall, conversions involving shrubs had the highest impact on (Figure 3).

3.1.2 Impact of land use conversions on carbon efficiency

The average CUE rankings are: ice/snow (0.429) > shrubland (0.348) > grassland (0.325) > bare land (0.323) >

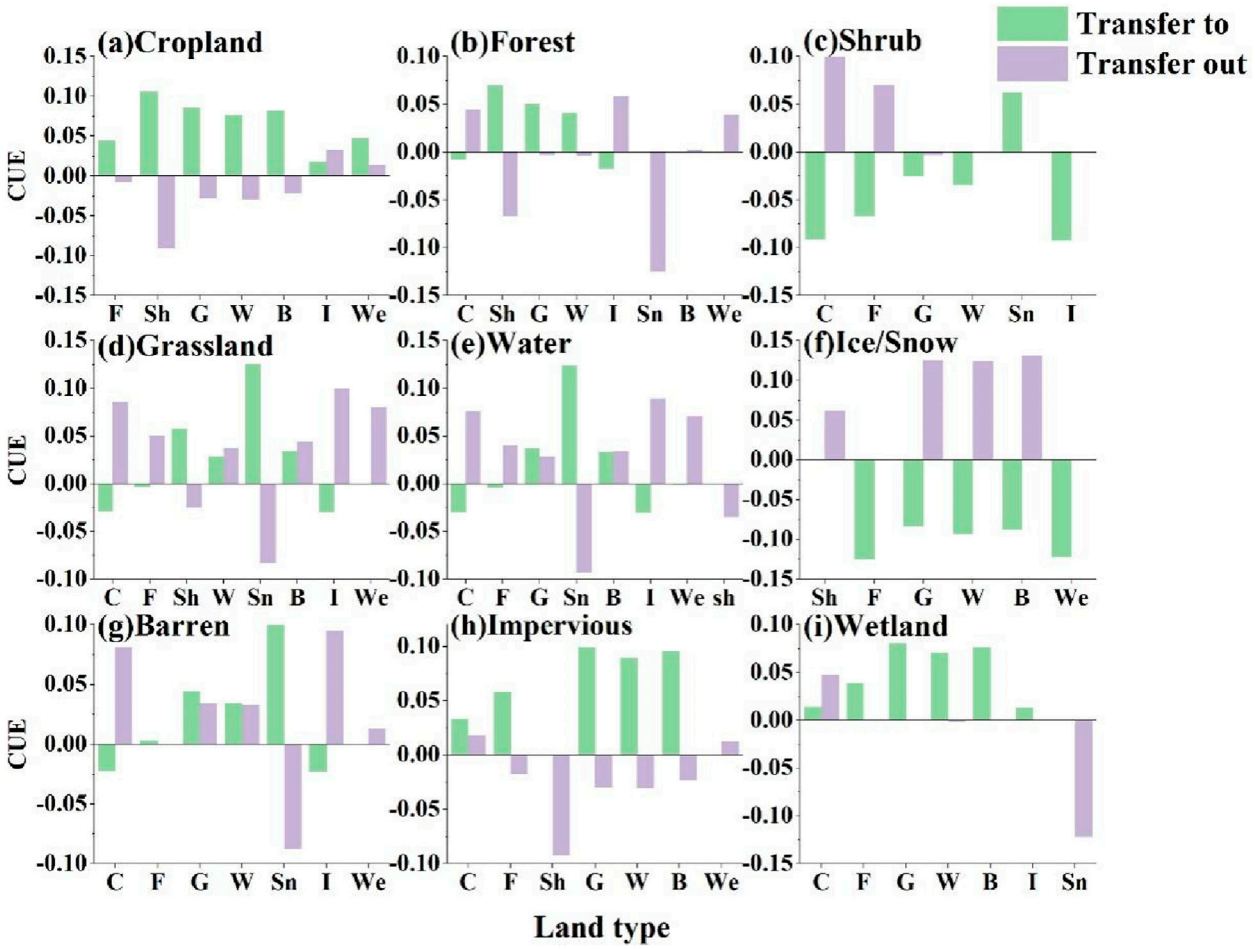


FIGURE 4
Changes in Carbon Use Efficiency (CUE) caused by land cover type conversions from 2000 to 2017 (C: Cropland; F: Forest; S: Shrub; G: Grassland; W: Water; Sn: Snow/Ice; B: Bare soil; I: Impervious surface; We: Wetland. "Conversion to" refers to changes in CUE when other land cover types convert to land cover type j; "Conversion from" refers to changes in CUE when land cover type j converts to other land cover types). **(A)** Cropland; **(B)** Forest; **(C)** Shrub; **(D)** Grassland; **(E)** Water; **(F)** Impervious; **(G)** Ice/Snow; **(H)** Barren; **(I)** Wetland.

water bodies (0.320) > forest (0.293) > wetland (0.292) > cropland (0.266) > impervious surface (0.261) (Figure 4). From 2000 to 2017, the conversion of wetlands to cropland decreased CUE by 0.05 (81.87% contribution), while grassland to wetland conversion reduced CUE by 0.08 (58.72%). Forest to grassland conversion increased CUE by 0.05 (0.63%), while forest to cropland decreased CUE by 0.008 (59.38%). Cropland to forestland conversion notably increased CUE by 0.44 (19.46%), showcasing forests' carbon storage advantage (Figure 5).

3.2 Effects of climate and vegetation dynamics factors on carbon-water use efficiency

3.2.1 Effects of climate and vegetation dynamics factors on water use efficiency

WUE shows positive correlations with VPD, temperature, and LAI across most land use types, with negative correlations observed for solar radiation in vegetation poor areas. NDVI shows a strong positive correlation with WUE for all but impervious surfaces, ice/snow, and bare land. Regional analysis indicates NDVI as the dominant factor influencing WUE (33.75% contribution), especially in the Yellow, Songliao, and Pearl River Basins. VPD follows with a 28.04% contribution, negatively impacting WUE across 66.21% of the area. Wind speed and specific humidity also significantly affect WUE (Figures 6–8).

3.2.2 The impact of climate and vegetation dynamics factors on carbon use efficiency

Climate factors are key drivers of CUE variability. Precipitation shows positive correlations with CUE for snow, impervious surfaces, and water bodies but negative correlations for forests and shrubs. Solar radiation is the primary controlling factor for CUE trends (36.46% contribution), followed by precipitation (26.72%) and LAI (24.71%). Temperature generally has a negative influence, especially in the inland and Yangtze River regions, while NDVI positively impacts 94.07% of the total area. (Figures 9–11).

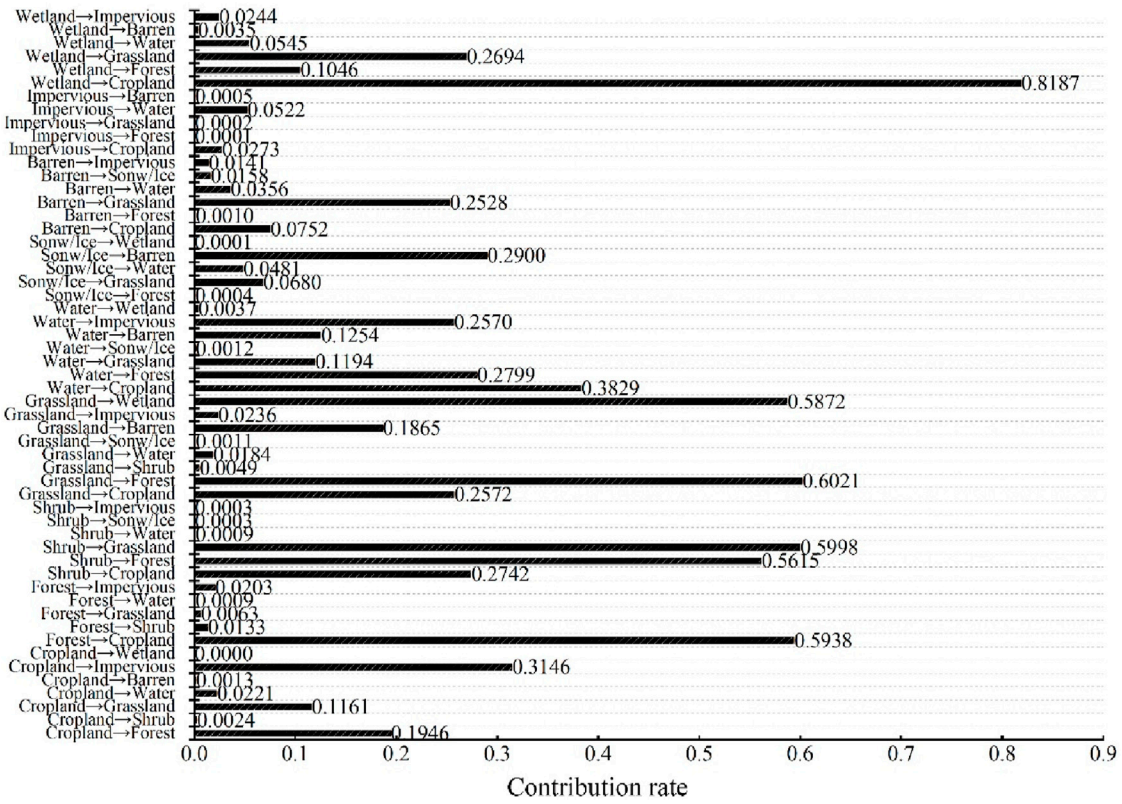


FIGURE 5
Contribution of land use change to changes in Carbon Use Efficiency (CUE).

4 Discussion

4.1 Factors influencing WUE (water use efficiency)

The spatial distribution of Water Use Efficiency (WUE) is primarily influenced by vegetation composition, land use types, and their spatial distribution (Tang et al., 2014). Favorable climatic conditions enhance vegetation growth, which, in turn, increases WUE. However, significant spatiotemporal variations in ecosystem WUE exist across different regions, and even within the same vegetation type, WUE can vary significantly across various areas. For instance, (Zhang et al., 2016) highlighted the spatiotemporal patterns of WUE in China's Loess Plateau from 2000 to 2010, ranking annual mean WUE from high to low as grasslands, forests, shrublands, and croplands. In contrast, Guo et al. (2019) analyzed WUE changes across various vegetation types in China from 1982 to 2015 and found that deciduous broadleaf forests exhibited the highest WUE among all vegetation types. Wang et al. (2020) similarly studied WUE changes on the Qinghai-Tibet Plateau from 1982 to 2015, concluding that evergreen broadleaf forests had the highest WUE. These disparities suggest that variations in climatic conditions and human activities, such as irrigation, significantly impact WUE.

Notably, human activities play a crucial role in determining WUE. Appropriate irrigation and fertilization practices can enhance WUE, potentially counteracting declines driven by climate and land use changes (Tian et al., 2011). A study in the Yellow River Basin of China demonstrated that converting grasslands to croplands or forests improved WUE, aligning with our findings (Sun et al., 2022). The transitions between forested and grassland areas, or between grasslands and barren ecosystems, indicate that conversions from high to low vegetation cover result in relative WUE decreases, and *vice versa*. For example, in the Hai River Basin, the expansion of artificial surfaces was a primary cause of WUE reduction, whereas the landscaping of bare land contributed to WUE increases. The dynamics of green spaces are thus a crucial factor affecting WUE changes (Zhao et al., 2019). However, in Northeast China, the conversion of farmland to forest ecosystems did not result in increased WUE, likely due to regional climatic conditions. In the arid western regions of North China, croplands exhibited higher WUE than forestlands, highlighting the complexity of influencing factors (Xiao et al., 2013).

Significant differences in WUE exist across various land cover types. Bare lands typically exhibit lower WUE due to minimal vegetation cover and high evaporation rates. Conversely, forests, characterized by developed root systems and dense foliage, generally demonstrate higher WUE compared to grasslands, croplands, and wetlands. In our study, forests exhibited higher WUE values than croplands and grasslands, consistent with previous research on WUE variations among different vegetation types (Khalifa et al., 2018). Variability in WUE values within grid units for different vegetation types may contribute to discrepancies in WUE values. These uncertainties can elucidate the differences between our study

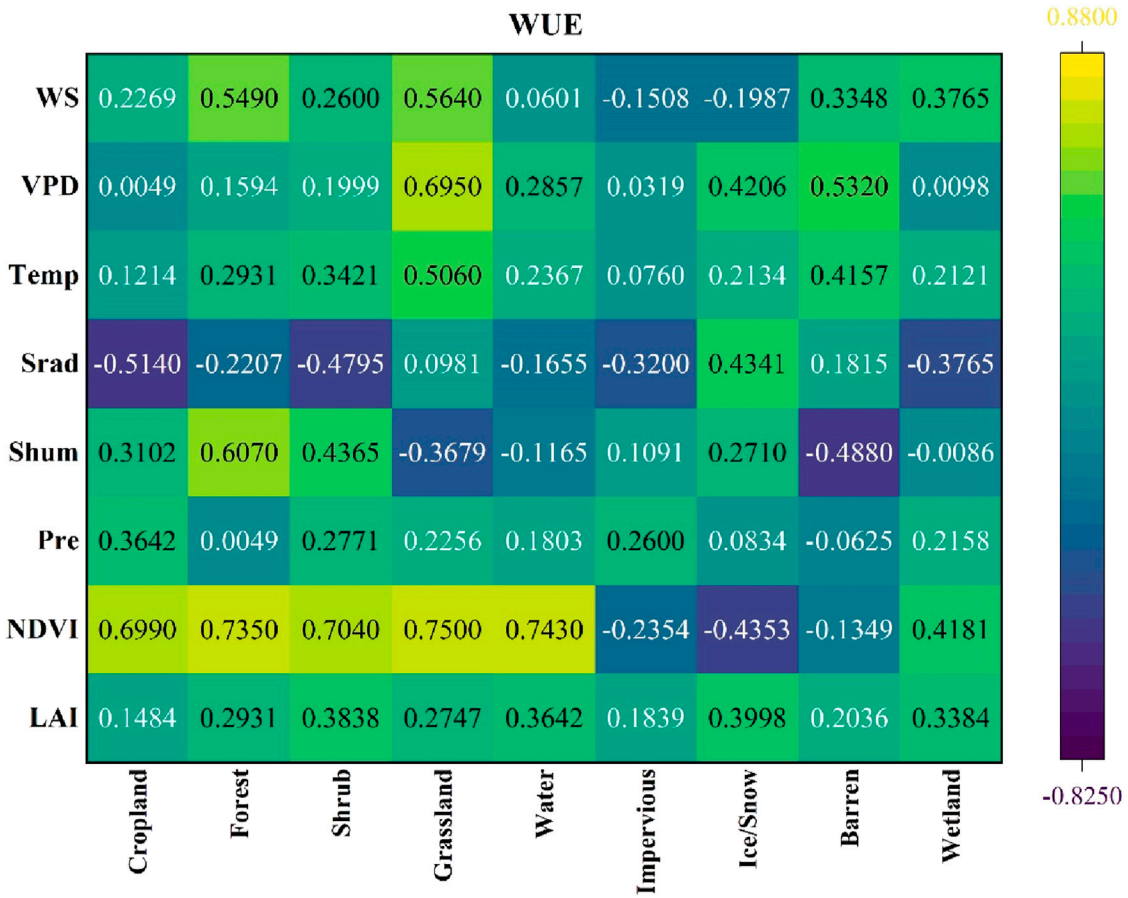


FIGURE 6
The correlation between Temp, Pre, Srad, Shum, VPD, WS, LAI, NDVI, and WUE across nine land use types.

and others. Overall, forestlands exhibit higher WUE than farmlands, indicating more effective utilization of available water resources through access to larger root zone areas, aligning with findings by (Khalifa et al., 2018).

Furthermore, Tian et al. (2010) demonstrated that WUE varies with land cover due to differences in carbon uptake and water consumption. Consequently, afforested and ecologically restored areas have become significant carbon sinks due to their strong carbon fixation capacity per unit of water consumed. Following the implementation of environmental restoration and watershed programs in the 1980s, WUE across land covers increased substantially, with trends in WUE over a 33-year period primarily driven by higher Net Primary Production (NPP). Previous studies on the impacts of watershed environmental restoration (Gebremicael et al., 2017; Nyssen et al., 2010) highlight the importance of ecological restoration and soil and water conservation measures in enhancing the sustainability of land and water resources.

Climate factors (temperature, precipitation, vapor pressure deficit, solar radiation, wind speed, and soil moisture) and vegetation dynamic factors (NDVI and LAI) influence variations in WUE by controlling both NPP and ET (Yang Y. H. et al., 2016). Overall, in China, NDVI has the greatest impact on WUE, as Sun et al. (Sun et al., 2016) suggest that vegetation adjusts stomatal conductance and water use efficiency in response to external environmental conditions during growth, maintaining normal growth and physiological functions. Notably, LAI and NDVI show an increasing trend in most regions of China, reflecting an overall "greening" (Tang et al., 2022). Our study results indicate that greening plays a dominant role in WUE changes in most regions of China, rather than climatic factors, consistent with previous research (Zhu et al., 2015). LAI is consistently positively correlated with WUE, attributed to its regulation of the ratio of NPP to transpiration; thus, as LAI increases, plants consume more water for NPP while soil evaporation decreases due to reduced solar radiation and precipitation reaching the land surface (Yang Y. T. et al., 2016).

The implications of our research findings for ecological and agricultural practices are profound. Enhancing Water Use Efficiency (WUE) is crucial for sustainable land management, particularly in the context of increasing water scarcity and climate change. Understanding the factors that contribute to improved WUE can guide effective irrigation strategies and vegetation management practices, thereby promoting ecological restoration and agricultural productivity. For instance, adopting management practices that favor specific vegetation types, such as deciduous broadleaf forests, may enhance the overall effectiveness of water resource management. Furthermore, strategies aimed at restoring

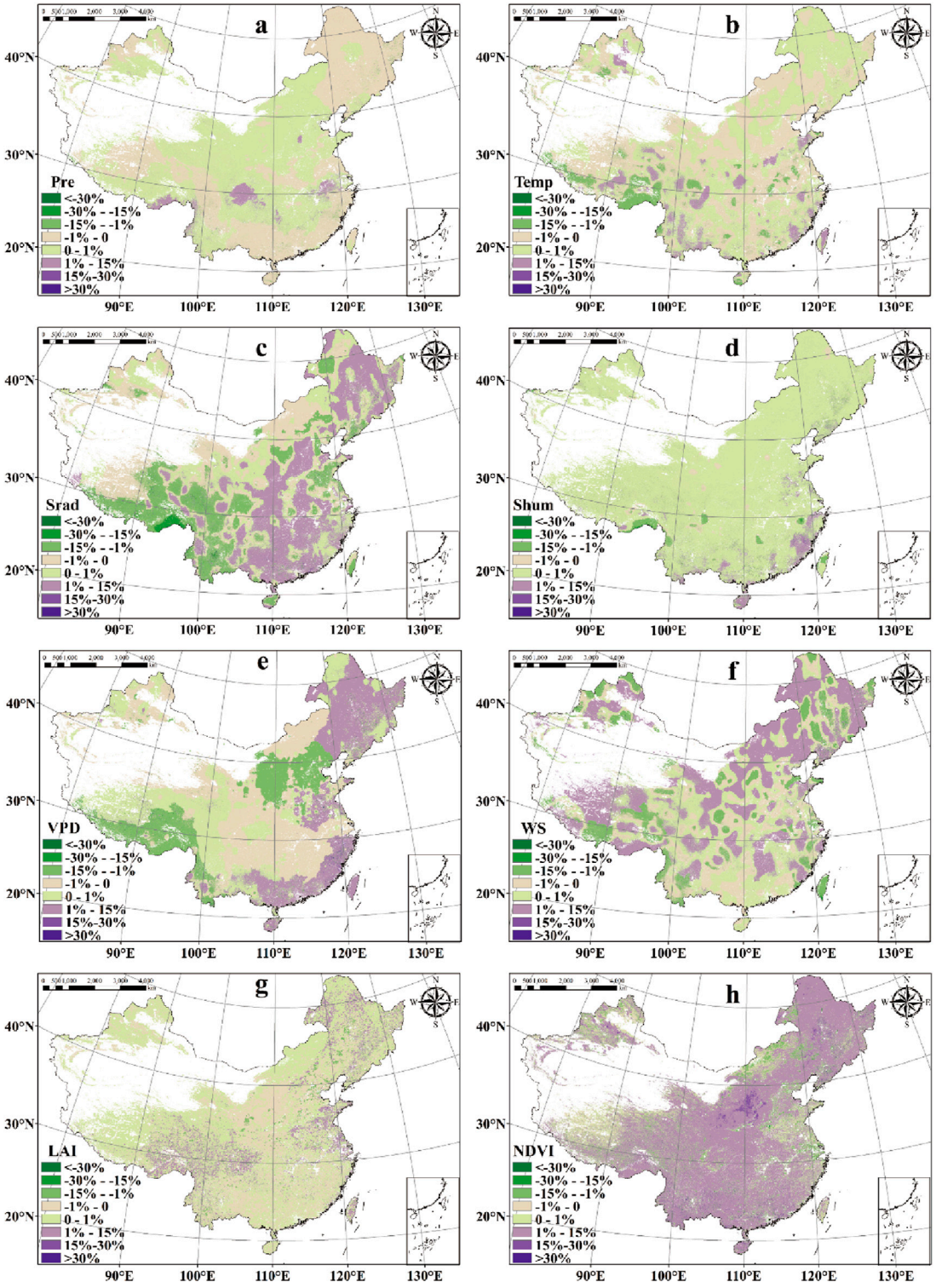


FIGURE 7
Contribution rates of different driving factors to the multi year average WUE. **(A)**, Pre; **(B)**, Temp; **(C)**, Srad; **(D)**, Shum; **(E)**, VPD; **(F)**, WS; **(G)**, LAI; **(H)**, NDVI.

and maintaining green spaces can positively influence WUE, thereby improving water resource utilization and ecosystem health. Changes in WUE directly impact land management practices. An increase in WUE can enhance the water use efficiency of agricultural systems, potentially reducing irrigation demands and alleviating water stress on surrounding ecosystems. This, in turn, may contribute to increased crop yields while conserving water resources. Conversely, in regions experiencing a decline in WUE, a

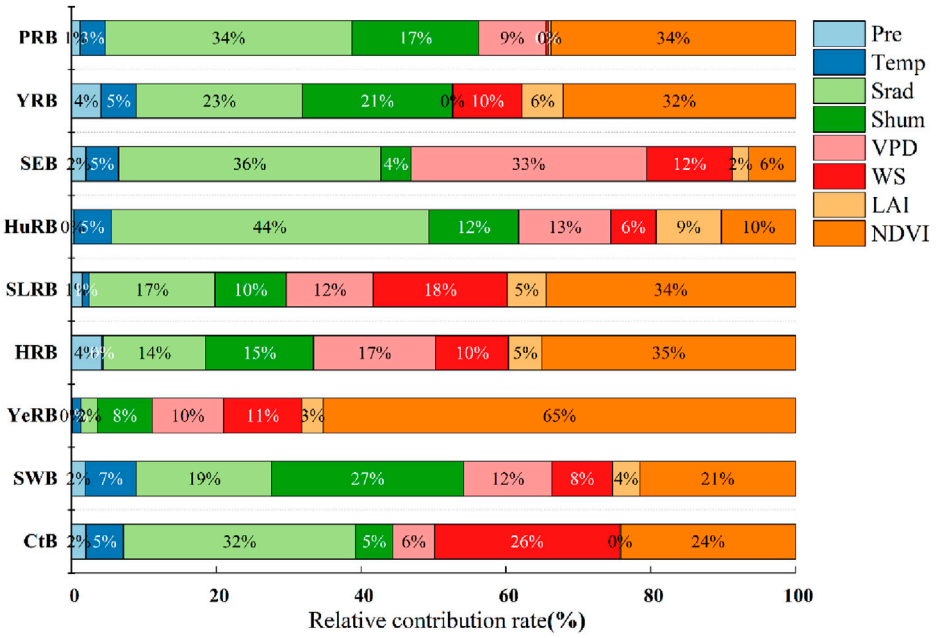


FIGURE 8
Relative contributions of climate factors and vegetation dynamics factors to WUE variations across nine major river basins in China.

reassessment of land use practices may be necessary to mitigate adverse effects on agricultural output and ecological health. Understanding the driving factors behind changes in WUE can inform policymakers and land managers in developing targeted interventions that align land use with sustainable water resource management. In summary, the findings of this study underscore the importance of integrating ecological factors into water resource management strategies. As water scarcity continues to pose challenges, enhancing WUE through scientifically-informed land management practices is vital for maintaining agricultural productivity and ecological integrity.

4.2 Factors influencing CUE (carbon use efficiency)

Analyzing changes in vegetation Carbon Use Efficiency (CUE) across the nine major river basins in China offers critical insights into the regional carbon cycle dynamics, highlighting the role of vegetation in regulating ecosystem carbon fluxes. CUE, which measures the ratio of carbon assimilated for growth and reproduction relative to the total carbon uptake, is a key indicator of ecosystem productivity and carbon sequestration potential. Zhao et al. (2021) observed that dense vegetation tends to exhibit lower CUE than sparse vegetation, and that forest CUE is generally lower than that of shrubs and herbaceous plants. These findings are consistent with our study, reaffirming the complexity of carbon allocation in various vegetation types. However, the mechanisms underpinning these differences may vary based on land use history, management intensity, and species composition, which future studies should explore further.

In contrast to Zhao et al. (2021) broad analysis of vegetation types, our study provides new insights into the climate-CUE relationship, specifically the influence of VPD (Vapor Pressure Deficit) on plant physiological processes. While Law et al. (2002) reported that vegetation CUE is positively correlated with precipitation and negatively correlated with temperature, our results refine this understanding by isolating the negative effects of temperature and VPD on CUE. VPD affects stomatal conductance, which in turn regulates CO_2 uptake, making it a critical factor in plant photosynthesis and respiration. This finding supports Liu et al. (2011), further underscoring VPD's role in limiting carbon assimilation under water-stressed conditions, which has far-reaching implications for future vegetation responses to increasing aridity and climate extremes.

A particularly novel finding of our study is the observed negative correlation between CUE and solar radiation (Srad), diverging from the conventional understanding that increased solar energy typically enhances biomass accumulation. While higher net solar radiation provides ample energy for photosynthesis, our results suggest that this relationship may be nonlinear, with diminishing returns in carbon use efficiency due to the increased respiration costs associated with high sunlight intensity. This sensitivity of respiration to solar radiation warrants deeper investigation, as it challenges previous assumptions about the direct benefits of solar energy on plant productivity, indicating that excess radiation may offset the gains from photosynthesis.

The role of NDVI in regulating CUE offers another important perspective. Previous studies, such as those by Polley et al. (2010), demonstrated NDVI's utility as a proxy for canopy development and its influence on CO2 fluxes. Our findings align with Liu et al. (2011), demonstrating a significant positive correlation between NDVI and CUE, thus highlighting the role of vegetation greenness and canopy structure in promoting carbon assimilation. This relationship emphasizes the importance of maintaining healthy, dense vegetation cover, particularly in regions where CUE is vulnerable to climatic stressors (Yashiro et al., 2010).

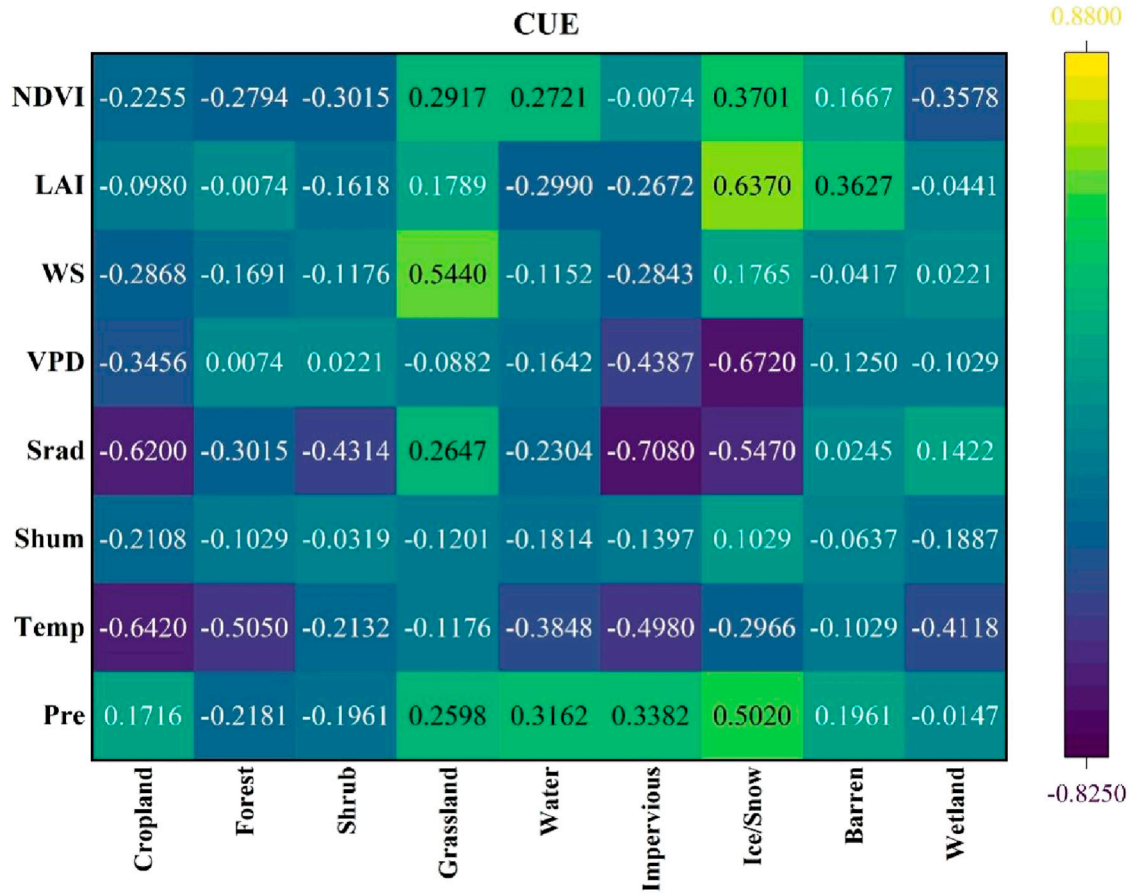


FIGURE 9
Correlation of Temp, Pre, Srad, Shum, VPD, WS, LAI, and NDVI with Carbon Use Efficiency (CUE) across nine land use types.

As climate change continues to exert increasing pressure on ecosystems, enhancing or maintaining Carbon Use Efficiency (CUE) through targeted land management practices is critical for sustaining ecosystem functions. Policymakers and land managers must account for the spatiotemporal dynamics of CUE when designing interventions to ensure that ecosystems remain productive and resilient under future climate scenarios. Incorporating CUE dynamics into effective land-use planning can enhance ecosystem services, such as carbon sequestration and water resource regulation, and contribute to long-term ecological sustainability. The findings of this study provide important insights into the factors influencing CUE, with implications not only for theoretical ecology but also for practical applications in land management and agriculture. By elucidating the complex relationships between CUE, climate, and vegetation dynamics, this study lays the foundation for more effective and sustainable management of ecosystems and agricultural landscapes in the face of ongoing environmental changes.

4.3 Carbon and water use efficiency in changing environments

The changes in Carbon Use Efficiency (CUE) and Water Use Efficiency (WUE) are closely related to land-use conversion and are also deeply influenced by climate change and internal climate variability. Global warming and fluctuations within the climate system jointly drive the complex changes in the carbon and water cycles of ecosystems. Therefore, it is necessary to further explore the role of these climatic factors in the discussion.

The impact of internal climate variability on regional climate and ecological processes cannot be overlooked. Ca et al. (2024) found that the pronounced warming on the Mongolian Plateau is partly attributable to the enhancement of internal climate variability, rather than solely to global warming. This internal variability not only alters regional water use efficiency by influencing temperature and precipitation patterns but may also affect carbon cycling processes by modulating ecosystem evapotranspiration. In this study, WUE shows significant correlations with climatic variables (e.g., temperature, VPD, and precipitation), particularly in regions with dense vegetation, where internal climate variability may amplify the effects of these climatic factors on WUE. For example, WUE in the Yellow River, Songliao River, and Pearl River Basins is significantly driven by NDVI and VPD, which is closely related to the regional climate fluctuations caused by internal climate variability. Therefore, future research should pay more attention to how climate variability affects carbon and water use efficiency in specific regions.

Under the context of global warming, changes in climate patterns profoundly influence carbon and water use efficiency.

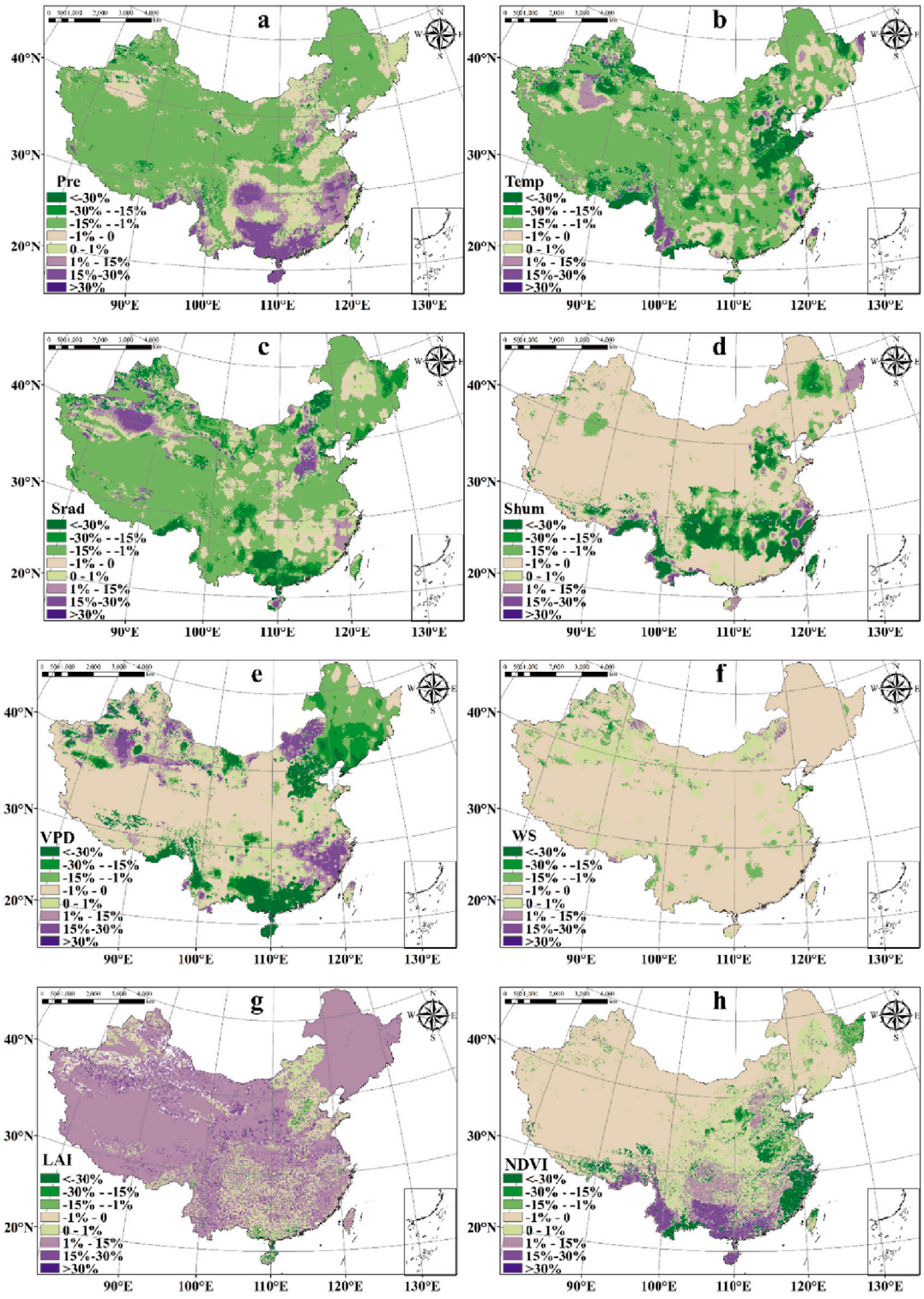


FIGURE 10
Contribution rates of different driving factors to the average annual Carbon Use Efficiency (CUE). **(A)**, Pre; **(B)**, Temp; **(C)**, Srad; **(D)**, Shum; **(E)**, VPD; **(F)**, WS; **(G)**, LAI; **(H)**, NDVI.

Chen et al. (2024) pointed out that global warming has strengthened the impact of the North Pacific Oscillation (NPO) on the development of ENSO, which means that changes in atmospheric circulation could significantly alter the distribution of precipitation and temperature, thus affecting water use and carbon storage in ecosystems. In this study, the positive correlations between WUE and temperature and VPD are significant across most land types, but in areas with sparse vegetation (e.g., bare land and ice/snow),

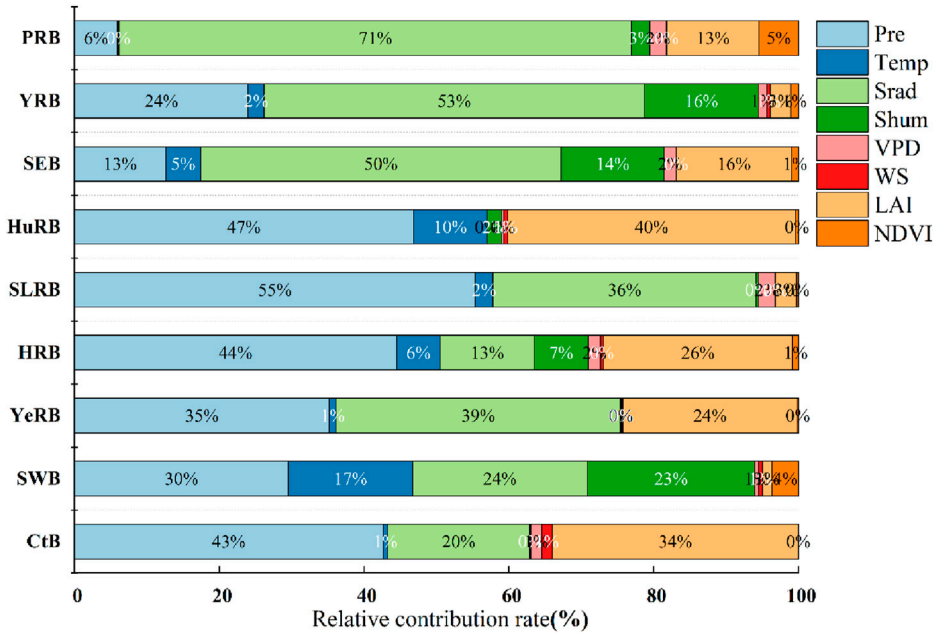


FIGURE 11
Relative contributions of various climatic and vegetation dynamic factors to changes in Carbon Use Efficiency (CUE) in nine major river basins in China.

negative correlations are observed, possibly reflecting the increasing water stress in these regions caused by global warming-induced drought. Moreover, the complex relationship between CUE, precipitation, and solar radiation suggests that global warming, by altering the long-term trends of these climatic variables, may have profound effects on the carbon use efficiency of ecosystems.

Future climate change scenarios (e.g., SSP245, SSP585) will further affect carbon and water use efficiency, especially under the dual influence of human activities and climate-driven land-use changes. The combined effects of global warming and internal climate variability could exacerbate the differences in carbon and water cycles across different land types. For example, this study found that the conversion of forests and shrublands has the greatest impact on WUE and CUE, highlighting the importance of ecological restoration and sustainable land management for enhancing carbon storage capacity and water use efficiency. Future research should further integrate simulations of climate variability and the impacts of extreme climate events to reveal the dynamic responses of carbon and water use efficiency under various climate change scenarios.

5 Conclusion

This study quantitatively analyzed the impact of land use conversion, climate, and vegetation dynamics on the carbon-water use efficiency (WUE) across nine major river basins in China. The primary controlling factors influencing WUE trends were identified as NDVI (Normalized Difference Vegetation Index) and VPD (Vapor Pressure Deficit). Contributions of Pre (precipitation), Temp (temperature), WS (wind speed), and LAI (Leaf Area Index) exhibited relatively dispersed positive and negative rates. Positive contributions of VPD were predominantly observed in the Songliao River basin, Huai River basin, Pearl River basin, and various southeastern river basins. Conversely, negative contributions of Srad (surface solar radiation) were mainly concentrated in inland river patches, the Huai River basin, and southwestern river basins. The Yellow River basin, Yangtze River basin, Pearl River basin, and Songliao River basin showed a dominant influence of NDVI, while Srad predominated in the southeastern river basins, Huai River basin, and inland river patches, and Shum (soil moisture) in the southwestern river basins. For Carbon Use Efficiency (CUE) trends, the main controlling factors were Srad and Pre. LAI, Shum, Temp, and VPD exhibited relatively dispersed positive and negative contribution rates. Negative contributions of NDVI were primarily observed in the Huai River basin and southeastern river basins, Pre in the Songliao River basin and Yellow River basin, and Srad in the Huai River basin, southwestern river basins, and southeastern river basins, with WS primarily influencing the Songliao River basin and Yangtze River basin negatively. The Huai River basin, Songliao River basin, Hai River basin, southwestern river basins, and inland river patches were dominated by Pre, while the Yangtze River basin, Yellow River basin, and Pearl River basin were dominated by Srad. This paper focused exclusively on analyzing the annual scale variations of WUE and CUE in Chinese river basins.

The study focused exclusively on analyzing the annual-scale variations of WUE and CUE in Chinese river basins. However, it underscores the crucial importance of understanding seasonal and monthly variations to comprehensively grasp the dynamic processes within the study area throughout the year. Therefore, future research should intensify analyses across different temporal scales to provide

a more scientific and comprehensive basis for decision-making in related fields. The limitations of this study lie in its focus solely on annual-scale WUE and CUE variations, without delving into the influences of seasonal and monthly changes on these efficiencies. To attain a more comprehensive understanding of ecosystem dynamics, future research should emphasize multi-temporal scale analyses, particularly concerning changes across different seasons and climate conditions. Additionally, given the impacts of human activities, future studies should integrate socio-economic factors to assess their potential effects on water resource management and sustainable agricultural practices.

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

GZ: Writing–review and editing. GW: Writing–review and editing.

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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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Investigation and future projections of warm rain during the winter monsoon in the Western Java Sea, Indonesia

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This study investigates the characteristics and future projections of warm rain during the winter monsoon (December–February; DJF) over the western part of the Java Sea (WJS), Indonesia, using satellite observations (TRMM), reanalysis data (ERA5), and model simulations (Atmospheric General Circulation Model; AGCM). The WJS, influenced by winter monsoon, experiences increased Sea Surface Temperatures (SST), which play a significant role in atmospheric dynamics and precipitation. Analysis of ERA5 data from 1950 to 2009 indicates a significant upward trend in SST for both the Indonesian region (slope 0.0070°C/yr) and the WJS (slope 0.0094°C/yr), with the highest SST increases occurring during DJF. Relating SST and Cloud Liquid Water Content (CLWC) during DJF shows a positive correlation coefficient (*R*) in the pathway of winter monsoon including the WJS. The *R* between cloud particles (CLWC, graupel and Cloud Ice Water Content; CIWC) and rainfall during DJF in WJS is higher for CLWC and rainfall which indicates the importance of CLWC. Warm rain processes, driven by CLWC, are evident, as TRMM observations of shallow rainfall align with CLWC spatial distributions. AGCM simulations successfully replicate the observed CLWC patterns, showing strong agreement with TRMM data in the western region of Indonesia including WJS. The study also compares low-level convergence patterns from ERA5 and AGCM data at 925 hPa, revealing similar trends in WJS, where convergence facilitates CLWC formation. The analysis of CLWC percentiles at an average of 1,000–700 hPa highlights a significant increase in CLWC over the pathway of winter monsoon, including the WJS, during DJF across 30-year intervals. The trends of CLWC for the Indonesia area and WJS also demonstrate the increasing value. These findings underscore the critical role of the winter monsoon in shaping warm rain processes in WJS and its implications for extreme weather events, such as flooding in land areas such as Jakarta.

KEYWORDS

climate change, SST, warm rain, CLWC, TRMM, AGCM

1 Introduction

Warm rain is a critical component of the hydrological cycle, especially in tropical regions, where it is the dominant precipitation mechanism. In the tropics, warm rain accounts for approximately 31% of total rainfall volume and covers 72% of the rain-affected areas (Lau and Wu, 2003). These statistics highlight its pivotal role in shaping tropical hydrology and climate dynamics. Warm rain forms in clouds with temperatures above 0°C through the droplet collision-coalescence process, bypassing the ice-phase Bergeron-Findeisen mechanism (Rogers

and Yau, 1989; Tao et al., 2012). Enhanced by high moisture availability and strong updrafts, this process sustains significant rainfall, impacting regional water resources, ecosystems, and weather patterns.

Climate change intensifies atmospheric and oceanic dynamics. According to the Intergovernmental Panel on Climate Change (IPCC, 2013), global sea surface temperatures (SST) have risen by approximately 2°C, coupled with a warming atmosphere with an increasing capacity to hold water vapor by about 7% per 1°C rise, as described by the Clausius-Clapeyron relation. This warming enhances cloud water content (CWC), which includes cloud liquid water content (CLWC) at temperatures above freezing and cloud ice water content (CIWC) at colder altitudes. Additionally, it increases rain liquid water content (RLWC), the liquid-phase component of precipitation derived from CLWC (Lebsock et al., 2008; L'Ecuyer et al., 2009; Suzuki et al., 2011; Zhang et al., 2020). As a result, warm rain events become more frequent, intensifying the hydrological cycle and leading to stronger and more frequent rainfall (Gao et al., 2021). Given the close relationship between CLWC and warm rain formation, this study uses CLWC as a proxy for warm rain occurrence.

Warm rain processes have been categorized into three types by Liu and Zipser (2009), namely isolated events, clouds adjacent to a rain system, and clouds embedded within larger clusters. Investigating these processes requires advanced observational tools, such as The Tropical Rainfall Measuring Mission (TRMM), which uses radar and radiometric sensors to monitor rainfall and cloud phases, including CLWC, graupel, and CIWC. This study employs TRMM data alongside simulations from the Meteorological Research Institute Atmospheric General Circulation Model (MRI-AGCM) to explore changes in warm rain processes through the CLWC, particularly in the Java Sea. The MRI-AGCM has been used to study the future rainfall change by Mizuta et al. (2012), Osakada and Nakakita (2018), and Mori et al. (2021) in Japan and East Asia region. It is a good opportunity to use and validate the MRI-AGCM data in Indonesia region.

The Java Sea, situated between Java, Sumatra, and Borneo, serves as a key region for studying warm rain processes due to its tropical maritime climate and strong monsoonal influences. During the winter monsoon, moist northeasterly winds enhance cloud formation and precipitation over the Java Sea (Chang et al., 2006), contributing significantly to regional water resources while also posing flood risks (Aldrian and Susanto, 2003). Local wind interactions create convergence zones that further intensify rainfall over the Java Sea (Ningsih, 2000; Matsumoto et al., 2017). These convective systems, particularly those developing at night and early morning, often propagate inland toward Jakarta due to land-sea interactions and moisture convergence. Moreover, during the northwest monsoon, prevailing easterly currents in Jakarta Bay can amplify coastal flooding when combined with heavy rainfall and storm tides (Shen et al., 2019; Lee et al., 2020).

Understanding warm rain dynamics is essential for assessing climate change impacts, improving rainfall predictions, and formulating adaptation strategies for regions increasingly vulnerable to extreme weather events. In the context of rising global temperatures, this study aims to investigate the future behavior of warm rain and its dynamics associated with convergence in tropical regions like Indonesia, with a particular focus on the Western Java Sea (WJS).

2 Research location, data, and method

2.1 Research location

The study utilizes a combination of observational data, reanalysis, and model simulations to analyze the characteristics and future projections of warm rain during the winter monsoon in the WJS. The WJS is in the northern part of Jakarta, a major city and former capital of Indonesia, making it a region of significant importance. Jakarta often experiences severe impacts during the winter monsoon due to increased rainfall (Nuryanto et al., 2021). This study focuses on the WJS within the coordinates 106°–110°E longitude and 4°–6°S latitude as shown in Figure 1.

2.2 Data

2.2.1 ERA5

The SST and convergence data used in this study are from the ERA5 dataset, developed by the European Centre for Medium-Range

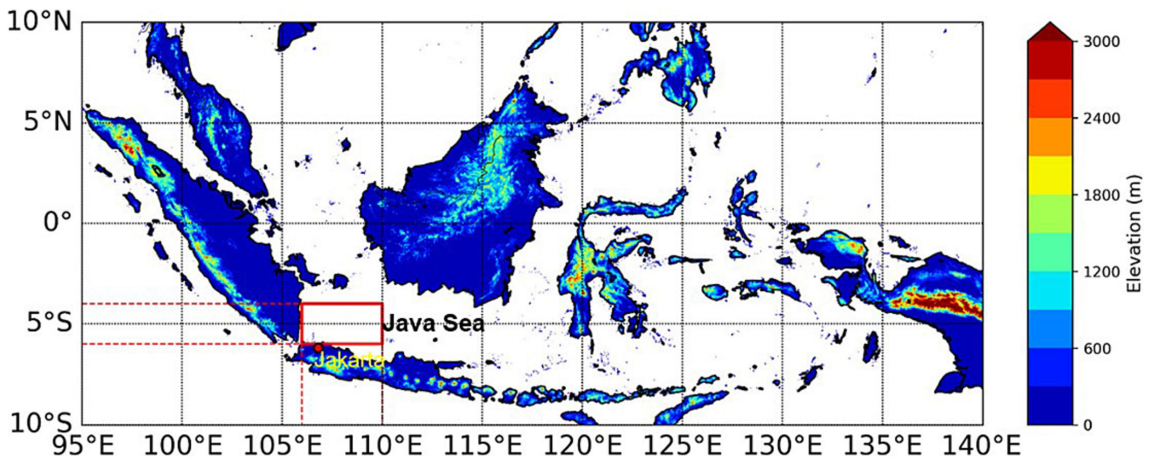


FIGURE 1
The topographic map of Indonesia highlights the WJS, marked by a red square box (coordinates: 6°S to 4°S, 106°E to 110°E). The red dot is Jakarta.

Weather Forecasts (ECMWF) under the Copernicus Climate Change Service (C3S). The SST data covers 60 years (1950–2009), while the convergence data spans 17 years (1998–2014), calculated from the zonal wind (U) and meridional wind (V) component (Hersbach et al., 2020). The shorter period of U and V is to align with TRMM, otherwise it would be nice to look at onvergence over a longer period, since ERA-5 is available from 1940 to present. ERA5 is a comprehensive global atmospheric reanalysis dataset that provides hourly estimates of a wide range of climate-related variables, encompassing atmospheric, land, and oceanic components. It provides global coverage with a horizontal grid resolution of 0.25° × 0.25° and a daily temporal resolution. The dataset includes 137 vertical levels, extending from the Earth's surface to an altitude of approximately 80 km. These high-resolution features make ERA5 an invaluable resource for analyzing climate dynamics across various spatial and temporal scales.[1]

2.2.2 TRMM

This study utilizes data from the TRMM satellite (TRMM, 2011a), a Low Earth Orbit (LEO) satellite designed to operate in tropical and subtropical regions between 35°N and 35°S (Kummerow et al., 1998). Specifically, the study uses the 3A12, 3A11, and 3A25 datasets, covering the period from 1998 to 2014 (17 years). The TRMM 3A12 dataset, derived from the TRMM 2A12 product, utilizes the TRMM Microwave Imager (TMI) sensor to detect various cloud particles, including CLWC, graupel, and CIWC. Additionally, the 3A12 data provides surface precipitation (rainfall) measurements. This dataset provides monthly data with a spatial resolution of 0.5° × 0.5° and 28 vertical layers with an interval ranging from 0.5 to 1 km (TRMM, 2011b). The 3A11 dataset analyzes the melting layer region, offering valuable information about this critical boundary. (TRMM, 2011c). Meanwhile, the 3A25 dataset, derived from the 2A25 product, utilizes radar observations to examine shallow (warm) rainfall (TRMM, 2011d). These datasets collectively provide critical insights into precipitation and cloud characteristics, with TRMM's observational area encompassing key tropical regions. Users can freely access and download the data from the NASA Goddard Earth Sciences Data and Information Services Center (GES DISC).[2]

2.2.3 AGCM

The model used in this study is the MRI-AGCM3.2, developed as part of the atmospheric component of the Earth System Model MRI-ESM1 (Yukimoto et al., 2012). MRI-AGCM3.2 builds on the previous version jointly developed by the Japan Meteorological Agency (JMA) and the Meteorological Research Institute (MRI) (Mizuta et al., 2012). It also includes minor updates from MRI-AGCM3.1, which was utilized in earlier 20-km resolution experiments (Kitoh and Kusunoki, 2008). This model features newly developed parameterization schemes for various physical processes designed collaboratively by JMA and MRI. These modular schemes, enable users to switch between updated and conventional implementations. For experiments conducted at a 20-km resolution, the models are designated as MRI-AGCM3.1S and MRI-AGCM3.2S, representing the super-high-resolution configurations. This research focused on CLWC parameters at altitudes between 1,000 and 700 hPa. According to Pruppacher et al. (1998), clouds in global climate model (GCM) simulations are typically assumed to consist entirely of ice at temperatures below approximately −40°C and entirely of liquid at temperatures above 0°C. However, in the tropics, systematic high biases are observed at all levels above 700 hPa (Li et al., 2018). The elevation data resolution for the Indonesian region is 1.25° × 1.25°, and the AGCM dataset provides monthly temporal resolution. Additionally, this study utilizes U and V to calculate convergence (Hersbach et al., 2020). The data can be accessed in the Data Integration and Analysis System (DIAS)[3].

2.3 Methodology

The methodology consists of six main components. First, the increase in SST data over Indonesia, including WJS was analyzed using ERA5 reanalysis data. Second, the analysis examined the relationship between SST and CLWC using TRMM data, applying correlation coefficient (R) methods. To resolve the differences in spatial and temporal resolutions between ERA5 SST data and TRMM CLWC data, linear interpolation adjusted the ERA5 data to match the TRMM grid resolution of 0.5° × 0.5°. Additionally, daily data was aggregated to a monthly timescale for consistency. Third, the R-value between warm rainfall and CLWC was investigated using TRMM data. Fourth, the performance of the AGCM was validated by comparing its output with satellite-derived CLWC data for past conditions, utilizing the R-value. Linear interpolation was also used to align the AGCM grid resolution of 1.25° × 1.25° with TRMM data. Since AGCM output includes only total CWC without distinguishing between liquid and ice phases, data below the freezing level (1,000–700 hPa) were used to represent CLWC. Fifth, the linkage between warm rain and atmospheric convergence at 925 hPa during winter monsoon was examined using convergence from the AGCM, along with the convergence value derived from ERA5. Finally, future projections of warm rain were assessed by analyzing AGCM-simulated CLWC data during winter monsoon, focusing on potential increases in warm rain associated with climate change.

3 Results and discussions

3.1 The increasing of SST in Indonesia

Figure 2 shows the spatial distribution of the 30-year climatology of SST around Indonesia, including the WJS region, highlighted by the red rectangle. Figure 2a represents the period 1950–1979, while Figure 2b covers 1980–2009. The analysis indicates a clear pattern of increasing SST across all regions of Indonesia, including the WJS, in 30-year increments. The increasing of SST will enhance moisture capacity as proposed by Clausius–Clapeyron relation, which predicts that the atmosphere's moisture-holding capacity increases by approximately 7% per 1°C rise in temperature (Martinkova and Kysely,

1 https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5

2 https://disc.gsfc.nasa.gov/

3 https://data.diasjp.net/dl/storages/filelist/dataset:650

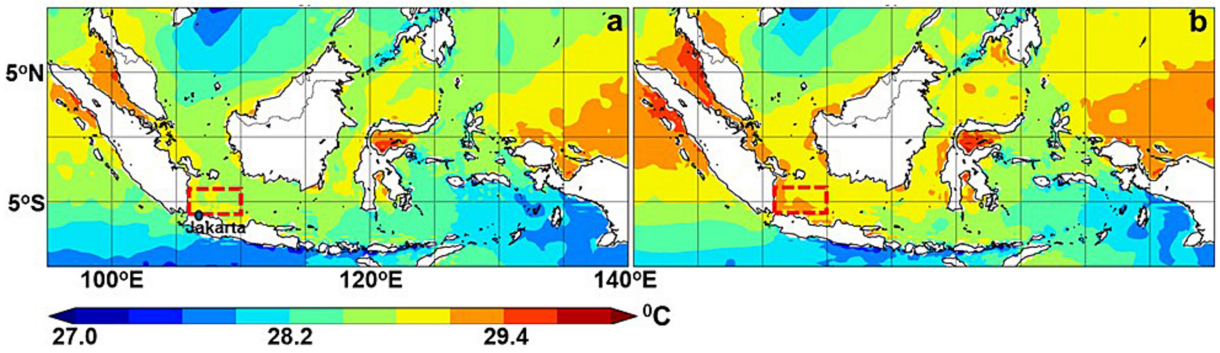


FIGURE 2
Spatial distribution of SST from ERA5 for the 30-year climatology of **(a)** 1950–1979 and **(b)** 1980–2009.

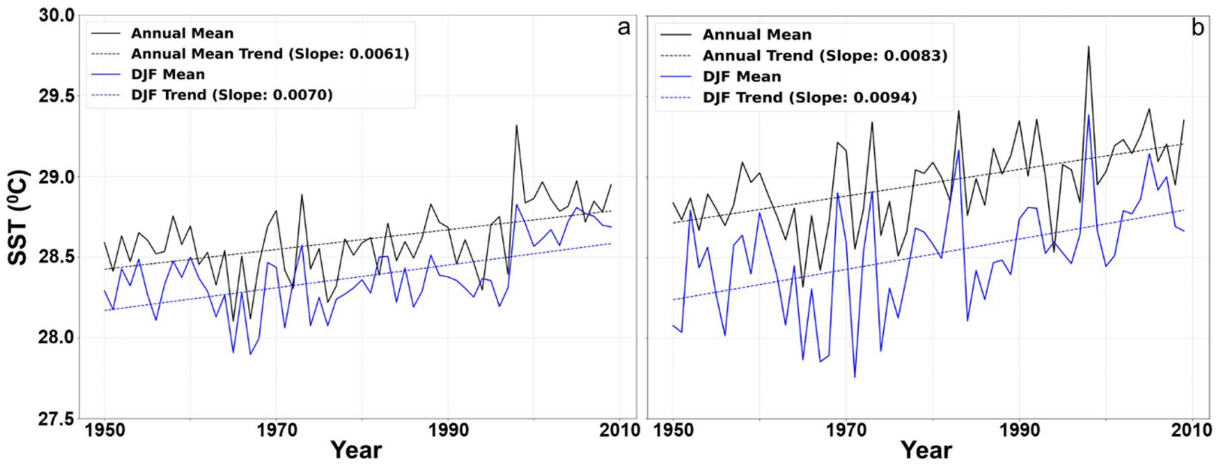


FIGURE 3
Time series of SST for annual and seasonal climatology in **(a)** Indonesia and **(b)** the WJS over 1950–2009 (60 years).

2020). A warmer atmosphere holds more water vapor, potentially resulting in heavier rainfall during the winter monsoon (Loo et al., 2015; Fahad et al., 2024). The warming trend in the WJS region can have significant implications for atmospheric dynamics, including the increased moisture-holding capacity of the air, which directly affects cloud formation and precipitation processes. These changes may significantly impact regional hydrology and weather patterns, such as increasing the risks of flooding and other climate-related effects, which could affect surrounding areas like Jakarta, located in the coastal region (Xu et al., 2019).

Figure 3 shows the annual and seasonal SST time series for Indonesia and WJS reveals a consistent warming trend across all seasons, with positive linear regression slopes indicating a steady increase in SST over the decades. The annual mean SST trend shows an increase of 0.0061°C/yr for Indonesia and 0.0083°C/yr for WJS, highlighting a slightly faster warming in WJS. Seasonal trends further support this pattern, with the most pronounced warming observed during the DJF period, where SST increases are 0.0070°C/yr for Indonesia and 0.0094°C/yr for WJS. This seasonal peak aligns with the winter monsoon, a critical period for precipitation processes. These consistent SST increases enhance the atmosphere's moisture-holding capacity, as per the Clausius–Clapeyron relation, which contributes to intensified cloud formation and precipitation processes. The WJS is slightly higher in SST warming compared to the broader Indonesian region, underscoring its sensitivity to climatic and oceanic dynamics, reinforcing the role of rising SSTs in amplifying warm rain and hydrological changes in the region. The highest increase in SST during DJF is very significant to be studied in Indonesian areas, especially in the WJS, due to its impact on this region. For the following analysis we will focus on the DJF to see the effect of the increasing SST. The DJF analysis also considers climate change, as indicated by the observed increase in SST.

3.2 Cloud particles profile and its correlation to SST and rainfall

The vertical profile of cloud particles over the Indonesian region reveals distinct characteristics of microphysical processes, as shown

in Figure 4. CLWC is concentrated primarily below 4 km, with a significant peak near the surface, indicative of warm cloud processes and abundant moisture in the lower troposphere. Li et al. (2013) found that the CLWC is concentrated around 3 km in the East and South China Sea. However, CLWC diminishes rapidly above 4 km as water droplets freeze into ice particles due to decreasing temperatures with altitude. Meanwhile, CIWC dominates the mid to upper troposphere, peaking around 12–14 km. This reflects the formation of ice-phase particles in colder atmospheric layers, driven by convective updrafts that transport moisture upward. CIWC decreases above 16 km, likely due to limited moisture and reduced ice nucleation at higher altitudes.

Graupel, characterized by its formation through riming processes, is prominent between 4 km and 14 km, with a peak concentration around 6–8 km. This range highlights intense convective activity, where supercooled water and ice crystals collide and grow into graupel. As part of warm and moist tropics, the Indonesian region supports vigorous convection, driven by processes such as those associated with the Intertropical Convergence Zone (ITCZ) and mesoscale convective systems (Houze and Churchill, 1987; Emanuel, 1994).

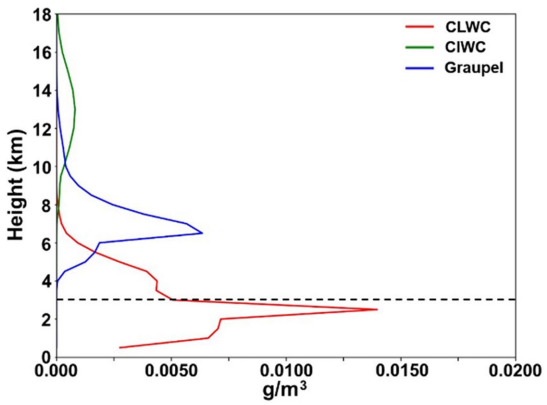


FIGURE 4
Average values of cloud particles (CLWC, graupel, CIWC) over the Indonesia region from 1998 to 2014.

The *R* between SST and CLWC, calculated for each grid cell every month, reveals complex spatial and seasonal dynamics, particularly over WJS. The annual climatology shows low or negative *R* values in most monsoon pathways, as seen in Figure 5a. This suggests that as SST increases, the average CLWC at lower levels (0.5–3 km) decreases, likely reflecting the convective nature of precipitation in this tropical region. Warmer SSTs enhance atmospheric instability, leading to deeper convection that facilitates the rapid conversion of CLWC into precipitation or transport to higher altitudes where it transitions into mixed-phase or ice particles. This dynamic results in reduced CLWC at lower levels. The averaging of wet and dry season processes further dilutes the SST-CLWC relationship, contributing to the overall weak *R* in the annual climatology across the monsoon pathway. In contrast, during the DJF climatology (Figure 5b), a pronounced positive correlation emerges in the northern part of Indonesia, influenced by the winter monsoon. This seasonal shift highlights the role of enhanced SST in driving atmospheric moisture and shallow convection, leading to higher CLWC during DJF. This pattern aligns with previous studies, such as Kodama et al. (2009), who linked warm SSTs to increased warm rain production, and Shah and Srivastava (2019), who reported positive SST-CLWC correlations in the Arabian Sea and central India. While this relationship is held in many regions, the WJS exhibits a weaker correlation, even during DJF. Despite increasing trends in SST and CLWC, the persistently low or negative R values in some parts of WJS suggest additional atmospheric processes at play, such as enhanced precipitation efficiency where cloud liquid water is more effectively converted into precipitation or shifts in cloud microphysics, including transitions from warm to mixed-phase clouds, which may limit CLWC accumulation.

Figure 6 highlights the *R* between rainfall and three cloud particle types: CLWC, graupel, and CIWC over WJS. Figure 6a demonstrates the highest *R* between rainfall and CLWC, indicating that CLWC in lower atmospheric layers contributes significantly to rainfall. Zhang et al. (2020) proposed that increasing CLWC leads to increased in rainfall. This strong relationship highlights the dominance of warm rain processes, particularly in tropical regions like Indonesia where abundant moisture and convective activity during winter monsoon drive rainfall formation. The efficient conversion of CLWC into raindrops under warm conditions is a characteristic feature of tropical convective systems. Figure 6b shows a moderate correlation between graupel

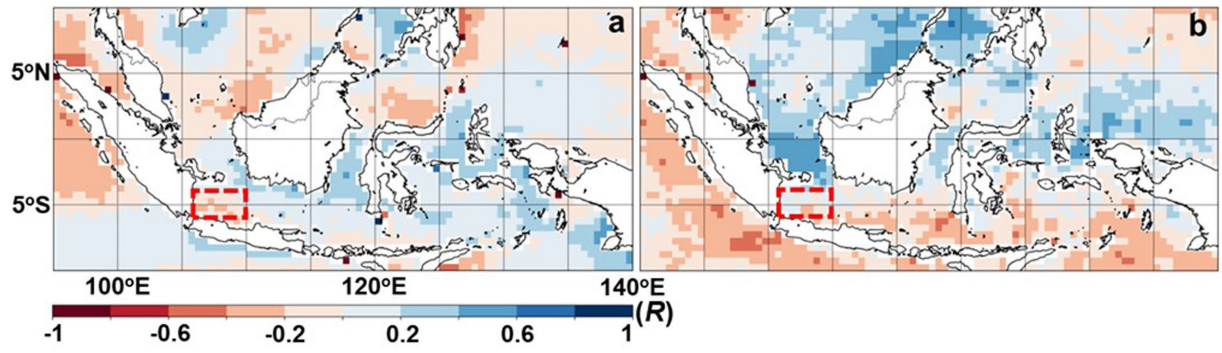


FIGURE 5
The spatial distribution of R between SST and CLWC at a height of 0.5 -3 km for **(a)** annual climatology and **(b)** DJF climatology from 1998 to 2014.

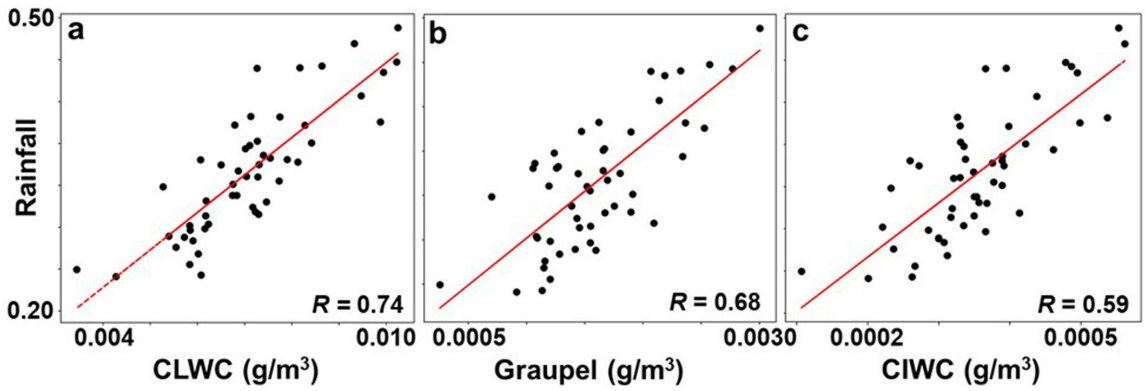


FIGURE 6
The *R* between **(a)** rainfall and CLWC, **(b)** rainfall and graupel, and **(C)** rainfall and CIWC during DJF from 1998 to 2014 over WJS.

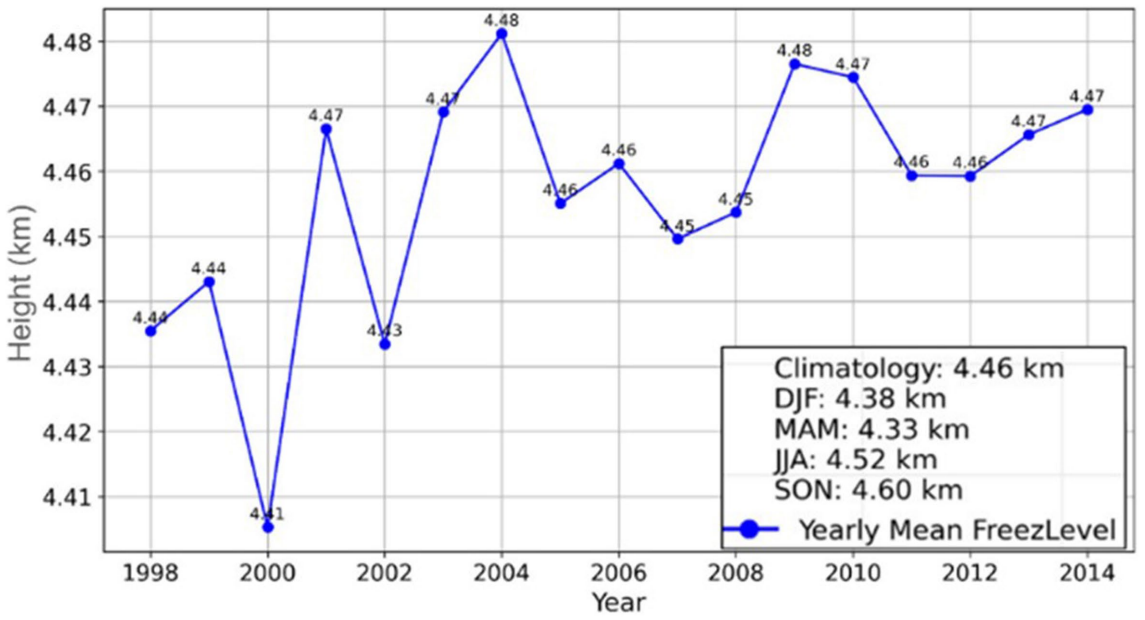


FIGURE 7
The annual and seasonal average freezing level over Indonesia from 1998 to 2014.

and rainfall, suggesting the importance of ice-phase processes in influencing precipitation. Graupel forms within convective clouds through riming, where supercooled liquid water freezes upon contact with ice particles, contributing to rainfall through melting as it falls into warmer layers. The role of graupel is particularly significant in mixed-phase clouds where strong updrafts prevail, indicating that it plays a secondary but crucial role in enhancing rainfall. Figure 6c displays the lowest correlation between CIWC and rainfall, which suggests that cloud ice contributes less directly to the rainfall. This weaker relationship likely stems from the fact that ice-phase particles must undergo additional processes, such as melting, to contribute to rainfall. The tropical environment, characterized by a warm and moist atmosphere, often supports warm rain mechanisms, thereby reducing the direct contribution of CIWC. Together, these correlations emphasize that while warm rain processes are dominant, ice-phase particles, particularly graupel, also play a critical role in modulating precipitation (Takahashi, 1976).

3.3 Warm rain investigation through CLWC

3.3.1 Freezing level average in Indonesia

Figure 7 reveals the annual average of the freezing levels observed by TRMM (data set 3A11) from 1998 to 2014 over the Indonesian region for annual and seasonal. It reveals a mean climatological value of 4.46 km, with a range between 4.41 and 4.47 km. Seasonal variability is evident, with the freezing level being notably lower during DJF at 4.38 km, likely due to the winter monsoon's influence, which brings cooler air masses and increased cloud condensation. Conversely, the freezing level is highest during SON at 4.60 km, followed by JJA at 4.52 km,

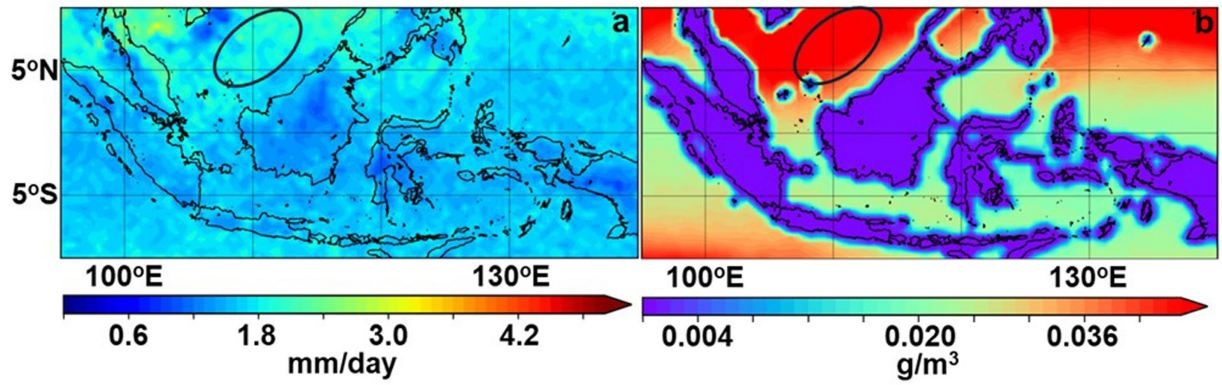


FIGURE 8
Spatial distribution comparison of **(a)** warm rainfall and **(b)** average CLWC at height 0.5–3 km from 1998 to 2014 for DJF. Black elliptical circle indicates the monsoonal pathway.

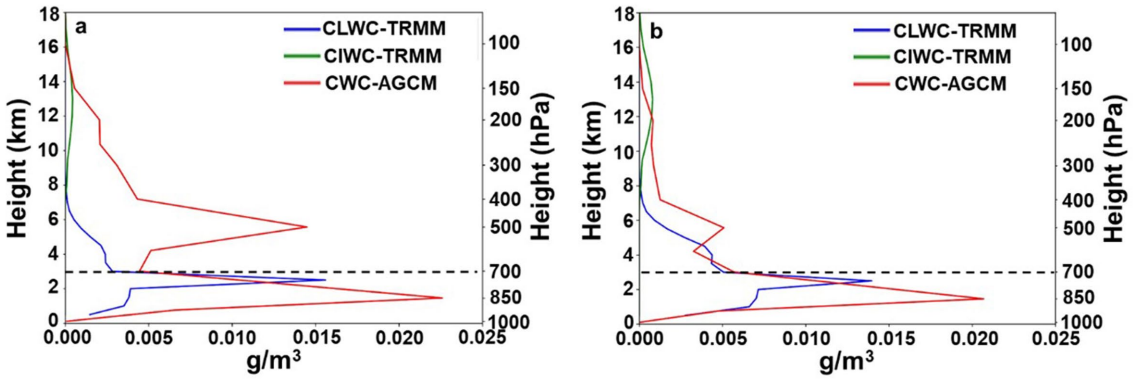


FIGURE 9
Comparison of the average vertical profiles of CWC, including CLWC and CIWC, between TRMM and AGCM from 1998 to 2014 for **(a)** annual climatology and **(b)** DJF climatology over the Indonesia region.

reflecting warmer atmospheric conditions during these periods. This seasonal fluctuation highlights the dynamic interaction between atmospheric temperature and precipitation processes in Indonesia, where lower freezing levels during DJF enhance warm rain formation by reducing the reliance on the ice-phase process. The melting layer height confirms the pattern shown in Figure 4, where CLWC decreases rapidly at around 4 km. The melting layer height is also a key factor in selecting CLWC data from TRMM and AGCM.

3.3.2 Warm rain investigation through CLWC

We investigate warm rain through a comparison of warm rainfall and CLWC. Warm rainfall refers to precipitation that occurs when radar reflectivity is detected below the freezing level. Figures 8a,b show the spatial distribution of warm rainfall and the average CLWC at heights of 0.5–3 km during DJF from 1998 to 2014, respectively. The results highlight the significant influence of monsoon dynamics on these parameters. During DJF, both warm rainfall and CLWC are more concentrated over maritime regions (black elliptical circle area), aligning with monsoon-driven moisture influx. Figure 8 shows a consistent relationship between warm rainfall and CLWC, as monsoonal circulation enhances cloud development, increases CLWC, and promotes warm rainfall. These findings underscore the critical role of monsoon dynamics in shaping seasonal variations in warm rain and CLWC over the WJS and surrounding regions.

3.4 Validating the output AGCM using satellite observation

3.4.1 Vertical profile comparison

A comparison of the average vertical profiles of CLWC/CIWC from TRMM and CWC from AGCM over the Indonesia region for 1998–2014 is shown in Figure 9a (annual climatology) and Figure 9b (DJF climatology). The figures highlight similarities and differences in the representation of cloud microphysics. Annual climatology indicates that the TRMM satellite captures both CLWC and CIWC, while the AGCM primarily simulates total CWC (the sum of CLWC and CIWC), which tends to be overestimated in the lower atmosphere (1000–700 hPa) compared to TRMM observations. TRMM CLWC is concentrated at lower altitudes, while AGCM exhibits higher CWC values throughout the vertical column. Focusing on the lower part of the atmosphere, at heights of 1,000–700 hPa (approximately 0–3 km), indicates that both datasets align well for CLWC, with TRMM offering more detailed differentiation between liquid and ice phases.

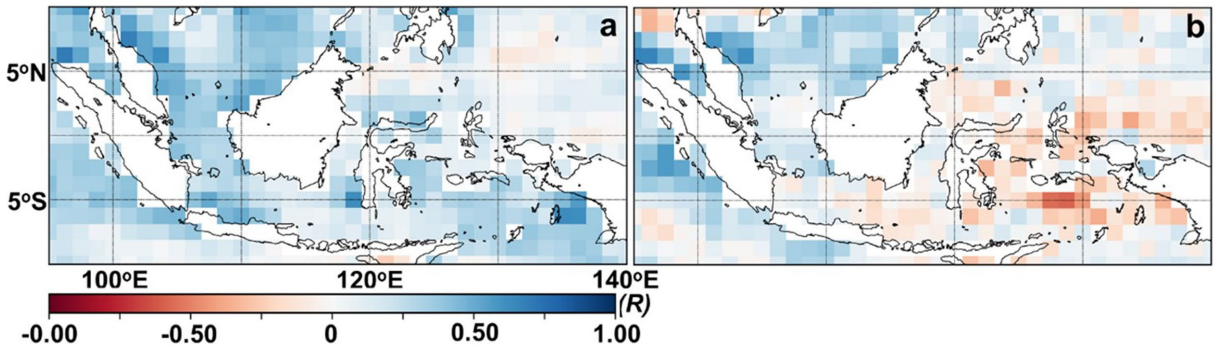


FIGURE 10
The spatial distribution of *R* between CLWC from TRMM and CLWC from AGCM at a height of 1,000–700 hPa for **(a)** annual climatology and **(b)** DJF climatology during 1998–2014.

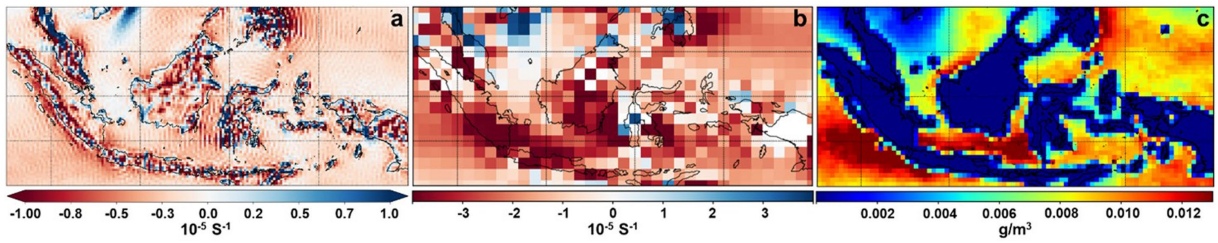


FIGURE 11
Convergence (divergence) is indicated as negative (positive) by **(a)** ERA5 reanalysis, **(b)** AGCM, and **(c)** CLWC from TRMM during the DJF for the period 1998–2014 at 925 hPa.

3.4.2 Correlation coefficient of CLWC distribution

The *R* between CLWC observed by the TRMM satellite and CLWC simulated by the AGCM, as shown in Figure 10, is calculated for each grid cell every month and reveals notable seasonal and annual variations. For annual climatology, higher correlations are observed in the northern parts of Indonesia, where atmospheric dynamics are simpler, allowing better agreement between AGCM and TRMM data. Seasonally, the DJF period demonstrates the strongest correlations, particularly over maritime regions, as the AGCM effectively simulates CLWC during DJF when atmospheric moisture is abundant. Moreover, while the AGCM performs better under stable monsoonal conditions, as seen in DJF, the lower correlations in eastern Indonesia highlight its limitations, suggesting that the model is more effective in the more humid western regions during the winter monsoon.

3.5 Investigating warm rain due to convergence during DJF

Figure 11 illustrates the 17-years (1998–2014) average distribution of convergence (divergence) indicated by negative (positive) value at 925 hPa from the ERA5 dataset (Figure 11a) and the AGCM model (Figure 11b), as well as the CLWC at 850 hPa observed by TRMM (Figure 11c) over Indonesia during DJF. The ERA5 and AGCM outputs show similar convergence patterns in the northern and western parts of Indonesia, with notable activity over WJS and areas near Western Sumatra. However, the AGCM model tends to overestimate convergence values compared to ERA5, especially over the WJS, indicating a potential bias in the model's sensitivity to atmospheric dynamics.

The relationship between convergence and CLWC is evident when comparing the convergence outputs to the CLWC from TRMM (Figure 11c). Regions such as Western Sumatra and WJS display a strong alignment, suggesting that areas of high convergence are associated with increased CLWC. This indicates that convergence plays a critical role in cloud development and precipitation formation in these areas. However, some regions show discrepancies in distribution, potentially due to differing atmospheric dynamics or limitations in capturing local-scale processes. Furthermore, these differences could be attributed to the varying spatial resolutions, as the AGCM's larger grid size may struggle to capture finer local-scale processes. These results suggest that convergence at 925 hPa has some influence on CLWC in the WJS, but the weak correlation indicates it may not play a significant role in driving warm rain formation during DJF. According to Compo et al. (1999) and Chang et al. (2005), cold surges during DJF often enhance atmospheric instability over the South China Sea, particularly in the region north of Borneo and along the Indo-China coast, due to intense low-level wind convergence at their leading edge. This low-level convergence also influences WJS, where it can increase precipitation, potentially affecting regional weather patterns and maritime conditions.

Overall, the similarities between ERA5 and AGCM in identifying key regions of convergence highlight the reliability of

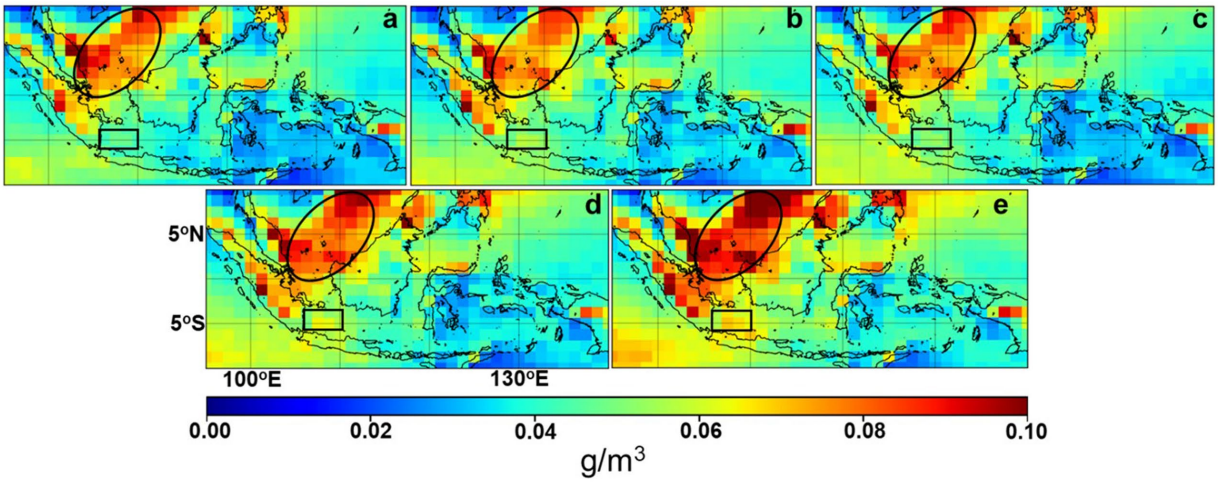


FIGURE 12
Temporal evolution of extreme CLWC values (95th percentile) at height 1,000–700 hPa during the DJF period from 1950 to 2099, shown at 30-year intervals: **(a)** 1950–1979, **(b)** 1980–2009, **(c)** 2010–2039, **(d)** 2040–2069, and **(e)** 2070–2099.

the model in capturing large-scale patterns. However, the AGCM's tendency to overestimate convergence values indicates the need for further refinement to enhance its accuracy. This is especially crucial in the dynamic atmospheric conditions of Indonesia, where accurately representing convergence is vital for understanding cloud processes and rainfall distribution. It should be noted that this study provides only a brief exploration of convergence during DJF, focusing on whether convergence or divergence dominates and examining the intensity of convergence. A more detailed investigation, utilizing data with higher temporal and spatial resolution, is necessary to gain a deeper understanding of convergence in the WJS.

3.6 Future projection of warm rain

This part investigates the future changes in warm rain by analyzing the spatial and temporal distribution of extreme CLWC values using model projections of AGCM. The focus is on understanding the potential increase in the 95th percentile (P95) of CLWC distribution under future climate scenarios. Figure 12 illustrates the temporal evolution of extreme CLWC values P95 during the DJF period from 1950 to 2099 at 30-year intervals, averaged over heights of 1,000–700 hPa, focusing on the western part of Indonesia, including the WJS. The results reveal a consistent increase in extreme CLWC values over time, particularly in WJS. From 1950–1979 (Figure 12a) to 2070–2099 (Figure 12e), the intensity of CLWC extremes becomes progressively stronger, reflecting the influence of warming temperatures and enhanced atmospheric moisture during DJF. This trend highlights the significant role of the winter monsoon in amplifying CLWC values in this region. The increased moisture availability due to rising SSTs and stronger monsoonal dynamics leads to more intense warm rain processes, as indicated by CLWC.

Figure 13 illustrates the increasing trend of extreme CLWC values (P95) over 150 years (1950–2099) at the 1,000–700 hPa pressure level, based on output from an AGCM. Two regions are represented, the Indonesia area (R1; red dots and trendline) and the WJS area (R2; blue crosses and trendline). Both regions show a consistent positive trend in CLWC over time, indicating a long-term increase. The slopes of the trendlines reveal a slightly steeper increase for the Indonesia area (0.00007182 g/m^3 per year) compared to the WJS (0.00004988 g/m^3 per year), suggesting regional differences in the rate of cloud water accumulation.

The stronger trend in the Indonesia area may be attributed to its geographical location near the equator, where convection and moisture convergence are more intense. In contrast, the WJS area shows a slightly weaker trend, possibly reflecting its relatively smaller influence from equatorial dynamics or local atmospheric conditions. This regional variability highlights the importance of local climate factors in shaping CLWC trends, which could be linked to broader climate change phenomena, such as increasing SST and changes in atmospheric circulation patterns. These increasing trends in CLWC have significant implications for future climate and weather in both regions. Enhanced CLWC may lead to more frequent and intense precipitation events, particularly over the Indonesia area, with the WJS and its surrounding regions being especially vulnerable, highlighting a heightened risk of extreme precipitation events in the future. This underscores the urgent need for improved climate adaptation strategies to mitigate the impacts of intensifying warm rain extremes in the region.

4 Conclusion

This study highlights the critical role of the winter monsoon in shaping warm rain processes over WJS, Indonesia, by leveraging TRMM satellite observations, ERA5 reanalysis data, and AGCM model simulations. The results reveal a significant upward trend in SST in the WJS and broader Indonesian region, with the highest increases occurring during the DJF period. This warming drives enhanced atmospheric dynamics, as evidenced by positive correlations between

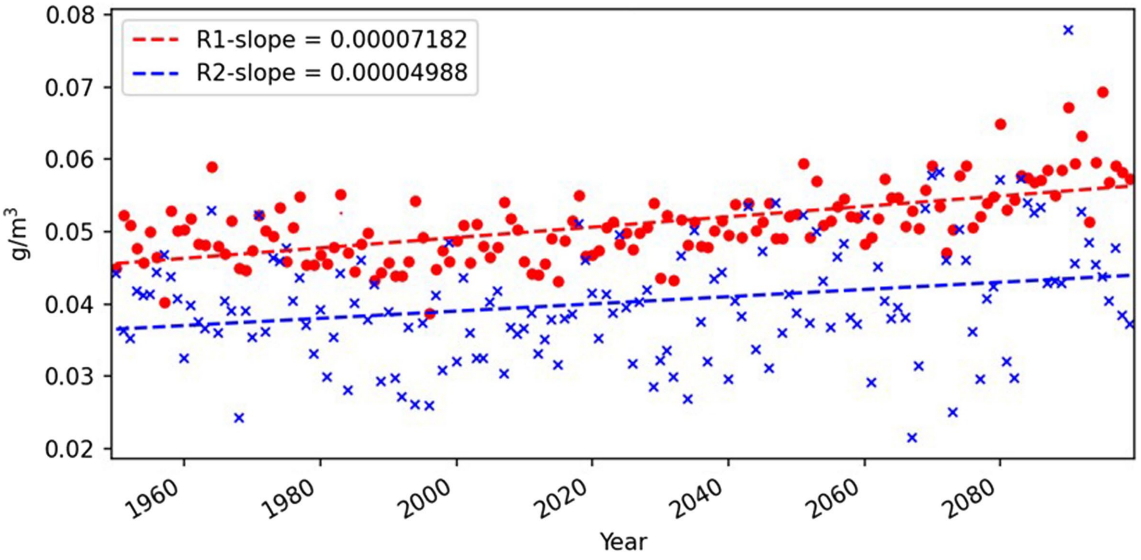


FIGURE 13
Time series and trendline of extreme CLWC values (95th percentile) during the DJF period from 1950 to 2099, averaged over Indonesia (R1; red dots and red dashed line) and WJS (R2; blue crosses and blue dashed line).

SST and CLWC, emphasizing the importance of CLWC as a proxy for warm rain processes. By serving as an indicator of liquid-phase precipitation development, CLWC provides critical insights into the mechanisms driving warm rain formation in the region.

Warm rain is identified as the dominant precipitation mechanism in the WJS, as evidenced by the alignment of warm rainfall patterns from TRMM observations with the spatial distribution of CLWC. AGCM simulations show strong consistency with TRMM data and ERA5 reanalysis, particularly in capturing low-level convergence patterns that promote CLWC formation. Analysis of CLWC percentiles at lower atmospheric levels (1,000–700 hPa) reveals a significant increase in CLWC over 30-year intervals along the winter monsoon pathway in Indonesia. Moreover, a 150-year trend indicates that CLWC will continue to increase in this region during DJF, reflecting the intensification of warm rain processes driven by the winter monsoon.

These findings underscore the potential for more frequent and intense precipitation events in the WJS and surrounding regions, raising concerns about extreme weather impacts, such as flooding in adjacent land areas like Jakarta. The study underscores the urgency of developing effective climate adaptation strategies to mitigate the risks associated with intensifying warm rain extremes in the region.

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 in the article/supplementary material.

Author contributions

WH: Data curation, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. EN: Conceptualization, Formal analysis, Funding acquisition, Supervision, Writing – review & editing.

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Cross-country comparative analysis of climate resilience and localized mapping in data-sparse regions

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Introduction: Climate resilience varies substantially across low-income countries (LICs), with agriculture often being the most vulnerable sector. Agricultural systems in these regions are typically rainfed, labor-intensive, and highly sensitive to climate variability. Yet, many LICs lack the high-resolution data needed to assess resilience at both national and local levels.

Methods: This study proposes a two-part framework to evaluate climate resilience across data sparse settings. First, sector-specific resilience is assessed at the national level using harmonized panel data and dynamic panel GMM regression models, incorporating structural and climate related variables. Second, a localized mapping approach is developed that integrates sparse field data with satellite-derived indicators. Agricultural productivity is interpolated across regions using kriging, a geostatistical technique optimized for sparse datasets. The study introduces the Resilience Asymmetry Surface (RAS) to visualize how resilience jointly depends on income and climate stress.

Results: National-level analysis shows that service sectors are more resilient to climate variability, while agriculture remains particularly vulnerable without structural support. At the local level, kriging-based interpolation of agricultural yield using sparse ground data and satellite inputs proves robust, with cross-validated RMSE values under 0.6 tons per hectare in Uganda, Kenya, and India. The RAS further highlights that similar climate exposures can yield very different resilience outcomes depending on a country's economic conditions.

Discussion: This framework enables climate-informed planning even in data-constrained environments by combining cross-country econometric modeling with localized spatial analysis. It supports national strategy development and targeted regional interventions, providing practical tools for policymakers seeking to strengthen resilience in LICs. The approach is scalable, cost-effective, and leverages openly available data, making it accessible for use in similarly under-resourced contexts.

KEYWORDS

climate resilience, cross-country analysis, agriculture, spatial interpolation, low-income countries

1 Introduction

The resilience of economic sectors to climate change varies widely across low-income countries (LICs), with agriculture often the most exposed and least protected. Agricultural systems in these regions are typically rainfed, labor-intensive, and highly dependent on seasonal patterns, making them particularly vulnerable to even moderate shifts in climate conditions (Habib-Ur-Rahman et al., 2022; Raza et al., 2019). Although resilience is influenced by structural and institutional factors—such as economic diversification, infrastructure, and governance—agriculture remains disproportionately affected due to its biophysical sensitivity and limited adaptive capacity (Leahy and Robins, 2021; Lemi and Hailu, 2019).

While a growing body of literature has examined climate resilience, most studies are focused on single-country contexts or subnational case studies. This narrow scope makes it difficult to understand broader patterns of vulnerability and adaptation, and limits the ability to draw general lessons across LICs (Badiane and Makombe, 2014; Dell et al., 2014). Cross-country comparisons, when available, often lack consistent data or fail to consider differences in sectoral exposure and structural capacity. A second limitation in the literature lies in the lack of localized assessments of climate impact, especially in rural agricultural regions. These areas are often excluded from large-scale analyses due to the scarcity of high-resolution, ground-based data. Yet they are also where climate stress hits hardest (Bussi et al., 2021; Portier et al., 2023). In many LICs, national datasets are incomplete or outdated, and field monitoring networks are thin or absent (Costella et al., 2023). As a result, most climate-agriculture models rely on either aggregate statistics or simulation-based estimates, with limited ground-truthing or spatial specificity (Wiréhn et al., 2017).

This study addresses these gaps through a two-part framework. First, it introduces a cross-country comparative analysis of sectoral climate resilience, combining meta-analysis with panel data models to capture structural and climatic drivers across different national settings. Second, it presents a localized climate-agriculture mapping approach, designed specifically for data-scarce environments. The method integrates sparse *in situ* data with high-resolution satellite imagery and uses kriging-based spatial interpolation to estimate agricultural productivity under climate stress at subnational levels.

Together, these methods provide a practical set of tools for planning and decision-making in regions where conventional data systems are weak. The framework supports both broad comparisons across countries and fine-grained vulnerability mapping within them. The key contributions of this paper are threefold:

1. A cross-country comparative framework for analyzing sectoral climate resilience, revealing shared patterns of vulnerability and adaptation across LICs.
2. A localized mapping technique that integrates sparse agricultural and climate data with satellite imagery using spatial interpolation, yielding fine-grained productivity estimates under climate variability.
3. Tools to support national and regional policy through evidence-based insights derived from harmonized datasets and spatial modeling tailored to data-scarce settings.

This work builds on recent developments in geospatial econometrics and spatial data science to extend climate resilience analysis beyond data-rich regions (Clingingsmith and Williamson, 2005; Diao et al., 2018). While both kriging and panel data models have been applied in climate-agriculture studies before, their integration into a resilience-focused framework for LICs remains rare. The study also includes cross-validation to evaluate interpolation accuracy—responding to previous critiques of empirical weakness in spatial modeling approaches (Wiréhn et al., 2017; Mazungunye and Punt, 2022).

2 Methodology

This study uses a two-part methodological approach to analyze climate resilience in low-income countries (LICs), focusing on both national-level sectoral patterns and localized agricultural productivity under climate stress. The first component is a cross-country statistical model that quantifies how different sectors—particularly agriculture, industry, and services—respond to climate variability across countries. The second component develops a spatial mapping method that estimates agricultural productivity in specific locations, even where field data are sparse, using satellite imagery and interpolation techniques. Together, these two components capture both the broad, structural patterns of resilience across countries and the localized vulnerabilities that standard macro-level models often miss.

2.1 Cross-country sectoral resilience estimation

The first part of the analysis is built around a panel data model that compares how economic sectors in LICs respond to climatic conditions over time. To support this, we first conducted a meta-analysis to compile sector-level economic and climate data from publicly available sources, including the World Bank, FAOSTAT, and national statistics bureaus. These datasets covered indicators such as agricultural yield, sectoral GDP, temperature, and rainfall.

Due to differences in how countries collect and report data, we applied harmonization steps to standardize coverage across years and countries. This included linear interpolation to address temporal gaps, and multiple imputation to account for missing values in economic and climate indicators (Badiane and Makombe, 2014; Lemi and Hailu, 2019). The model estimates sectoral resilience—defined here as the ability of a sector to maintain performance in the face of climate stress. This is done using the System Generalized Method of Moments (GMM), which is well-suited for dynamic panels with unbalanced observations and endogenous regressors (Dell et al., 2014). The estimated equation is:

$$R^{s}_{i,t} = \beta_0 + \beta_1 X_{i,t} + \beta_2 Z_{i,t} + \varepsilon_{i,t} \quad (1)$$

In Equation 1, $R^{s}_{i,t}$ represents the resilience of sector s (such as agriculture) in country i at time t. The term $X_{i,t}$ includes climate-related variables, such as average temperature and precipitation, while $Z_{i,t}$ includes structural controls like the share of the labor force in agriculture, infrastructure access, or trade exposure. The

coefficient β_1 thus captures the impact of climate variability, while β_2 accounts for how national conditions shape sectoral performance under stress. This model allows us to isolate the influence of climate factors from broader structural differences, offering a more accurate understanding of where and why some sectors or countries are more resilient than others.

2.2 Localized climate-agriculture mapping using sparse data

While the panel model captures cross-country trends, it cannot reveal what is happening at more granular, subnational levels—especially in rural farming regions where vulnerability is highest. To address this, we developed a localized mapping approach that estimates agricultural productivity using limited ground data and satellite imagery. Field-level yield data were collected from open-access sources, including government reports, agricultural research stations, and survey datasets, with geographic coverage focused on Uganda, Kenya, and India. These data are often irregular in spacing and coverage, especially in remote or resource-poor regions (Bussi et al., 2021; Portier et al., 2023). To enhance spatial coverage, we integrated these sparse field points with satellite-derived indicators, including rainfall data from CHIRPS and vegetation indices (NDVI) from the MODIS platform (Raza et al., 2019; Mazungunye and Punt, 2022). We then modeled agricultural productivity at any location (x, y) as a function of local climate conditions and structural features of the land

$$P(x,y) = \alpha + \beta_1 C(x,y) + \beta_2 Z(x,y) + u(x,y) \tag{2}$$

In Equation 2, $P(x, y)$ is the observed or estimated productivity (e.g., tons per hectare), $C(x, y)$ includes spatially varying climate indicators such as precipitation and temperature, and $Z(x, y)$ accounts for local controls like land cover, soil type, or elevation. The error term $u(x, y)$ captures local factors not explicitly modeled. Because field data are only available at scattered locations, we used spatial interpolation to estimate productivity values at unsampled points. We selected kriging as the primary method because it explicitly models spatial correlation between known points through a variogram, and offers statistically optimal estimates under sparse-data conditions (Wiréhn et al., 2017). The kriging estimate for productivity at any location (x, y) is given by:

$$\hat{P}(x,y) = \sum_{i=1}^{n} \lambda_i P(x_i, y_i) \tag{3}$$

Here, $\hat{P}(x, y)$ is the predicted productivity at the unsampled location (x, y), and $P(x_i, y_i)$ are known productivity values at nearby sampled locations. The weights λ_i are derived from the spatial correlation structure (the variogram) and ensure that points closer and more correlated to (x, y) are given greater influence in the prediction.

We benchmarked kriging against two alternative methods: inverse distance weighting (IDW) and spline interpolation. Across all cases, kriging produced better predictive performance, especially in regions with few observations. To test accuracy, we used five-fold cross-validation, rotating the withheld data used for validation in each fold. The root mean squared error (RMSE) was used as the evaluation metric, and results confirmed kriging's robustness in sparse-data environments (Wiréhn et al., 2017; Mazungunye and Punt, 2022).

By combining spatial econometric modeling with satellite imagery, this approach allows us to create high-resolution maps of agricultural productivity that are both data-efficient and grounded in observed patterns. These maps are particularly useful for identifying vulnerable regions where climate adaptation measures, such as irrigation or crop diversification, may be most urgently needed—even in places where no systematic field data exist.

3 Cross-country and localized insights into resilience

The results of this study are grounded in the methodological framework described earlier. The goal is to reveal how climate variability affects economic sectors across countries, and more specifically, how agricultural productivity varies within countries where data are sparse. These results provide both a bird's-eye view of resilience patterns across LICs and a close-up of vulnerable farming zones at the subnational level. The aim is not only analytical, but also practical—to support decision-making in contexts where limited data often constrain planning.

We begin by analyzing how resilience differs across sectors and countries. Using harmonized panel data and the regression model previously introduced, we estimate how responsive each economic sector is to changes in temperature and rainfall, controlling for structural conditions like labor force composition and infrastructure. This estimation, shown in Equation 4, follows Equation 1 from the methodology:

$$R^s_{i,t} = \beta_0 + \beta_1 X_{i,t} + \beta_2 Z_{i,t} + \varepsilon_{i,t} \tag{4}$$

The results show clear and consistent trends. Agriculture emerges as the most climate-sensitive sector, with resilience scores decreasing sharply in response to increased temperature volatility and declining rainfall. By contrast, service sectors remain relatively insulated, likely due to their lower dependency on weather-sensitive inputs and infrastructure. These findings confirm earlier observations from the literature (Habib-Ur-Rahman et al., 2022; Raza et al., 2019; Lemi and Hailu, 2019), which emphasize the climate exposure of primary sectors in low-income contexts.

Beyond individual countries, we group countries based on how their sectors respond to climate variables. Cluster analysis on the estimated resilience coefficients reveals three dominant country types. The first cluster includes countries that show low resilience across all sectors and are also exposed to high climatic variability—typically fragile states or post-conflict economies. The second group features stronger performance in industrial and service sectors but still shows weak agricultural resilience. This pattern often aligns with countries undergoing structural transition, where agriculture remains under-invested. The third group shows a more balanced profile, with moderate climate exposure and medium to high resilience across sectors. This categorization offers a useful way to tailor adaptation strategies. For example, countries in the first cluster may need foundational

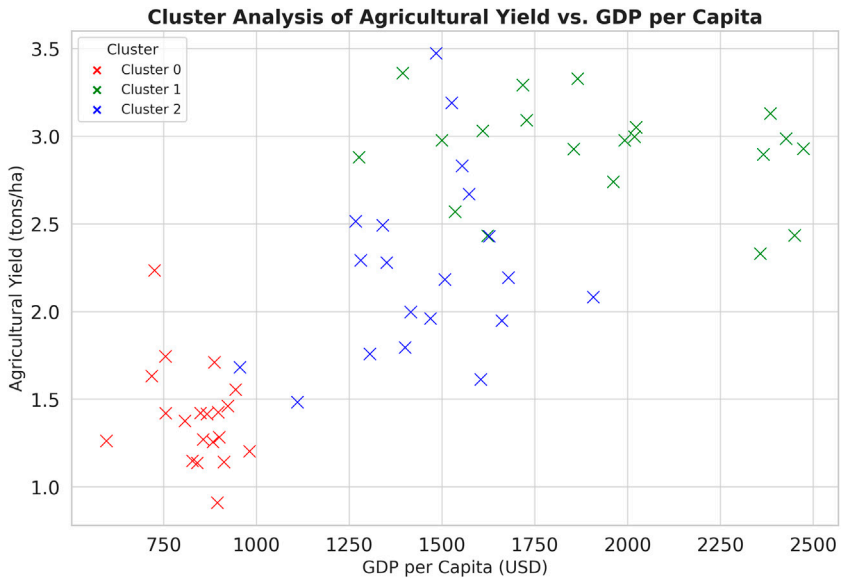


FIGURE 1
Cluster Analysis of Agricultural Yield vs. GDP per Capita.

support in infrastructure and governance, while those in the second may benefit from targeted agricultural innovation and finance programs (Badiane and Makombe, 2014; Diao et al., 2018).

However, while cross-country trends are useful, they cannot capture the heterogeneity within countries. National averages often mask sharp local disparities in how climate affects productivity, especially in rural farming regions. To address this, we apply a spatially explicit mapping approach, (c.f. Equation 5) based on the geospatial econometric model defined in Equation 2

$$P(x,y) = \alpha + \beta_1 C(x,y) + \beta_2 Z(x,y) + u(x,y) \tag{5}$$

Here, $P(x,y)$ is the agricultural productivity at a specific location, $C(x,y)$ includes satellite-derived climate indicators like rainfall and temperature, and $Z(x,y)$ includes structural controls such as land use or soil properties. This model links environmental conditions with yield outcomes in a statistically consistent way. Yet, in many LICs, ground-level agricultural data are too sparse to allow direct estimation of productivity across the entire territory. To overcome this, we use kriging—a spatial interpolation method that leverages observed data points and their spatial correlation structure to estimate values in unsampled areas. This is formalized in Equation 3:

$$\hat{P}(x,y) = \sum_{i=1}^{n} \lambda_i P(x_i, y_i) \tag{6}$$

From Equation 6, each weight λ_i is derived from a variogram that captures how productivity measurements at different points relate spatially. Kriging has been shown to outperform simpler techniques like inverse distance weighting or spline interpolation in agricultural settings with limited field observations (Wiréhn et al., 2017; Mazungunye and Punt, 2022). We apply this model to three countries, using 150 field data points per country. Satellite data are used at a 1 km^2 resolution to enrich spatial coverage. The output is a continuous surface showing predicted productivity across entire regions, including areas without direct measurements. To assess performance, we use five-fold cross-validation and compute RMSE. The results are promising: Uganda shows an average RMSE of 0.43 tons/ha, Kenya 0.51, and India 0.37. These values indicate that even with sparse data, the model can reliably estimate yield outcomes.

Crucially, the maps produced through this method are not just technical artifacts—they are decision tools. They highlight zones where productivity is consistently low, pointing to areas where climate adaptation efforts should be prioritized. Conversely, they also reveal areas that perform well under stress, which may offer lessons in resilience that can be scaled or replicated elsewhere. This kind of spatial intelligence is especially valuable for planning investments in irrigation, extension services, or targeted subsidies, particularly in places where official statistics are outdated or unavailable (Bussi et al., 2021; Costella et al., 2023). To operationalize the mapping approach, we developed a simple algorithmic framework that integrates data collection, model estimation, interpolation, and visualization into a repeatable workflow. The process starts with merging satellite data and local yield observations into a GIS platform. Next, model coefficients are estimated using ordinary least squares. These are then used in the kriging interpolation to predict productivity across space. The final step involves mapping the results to identify vulnerable and high-performing zones.

The strength of this approach lies in its simplicity and adaptability. It works with the kind of data that many low-resource countries already have access to—limited field observations and open-source satellite imagery. Yet, by structuring and modeling these inputs carefully, it yields outputs that can guide both national strategies and local interventions. This combined framework—statistical resilience modeling at the national level and localized mapping at the subnational level—offers a

TABLE 1 PanelOLS estimation of agricultural yield.

Dep. Variable	Agricultural Yield	R-squared	0.0340
Estimator	PanelOLS	R-squared (Between)	−0.2887
No. Observations	124	R-squared (Within)	0.0340
Cov. Estimator	Robust	R-squared (Overall)	−0.2634

Variable	Coefficient	Std. Error	T-stat	P-value	95% CI
Temperature	−0.0191	0.0157	−1.22	0.226	[-0.050, 0.012]
Precipitation	0.0003	0.0001	1.69	0.094	[-0.00004, 0.0005]
GDP per capita	0.00006	0.0001	0.47	0.641	[-0.0002, 0.0003]
Labor force in agriculture	−0.0008	0.0037	−0.22	0.823	[-0.0081, 0.0065]

TABLE 2 PanelOLS estimation: Climate and sectoral predictors of resilience.

Dep. Variable	Resilience	R-squared	0.9153
Estimator	PanelOLS	R-squared (Between)	0.9921
No. Observations	88	R-squared (Within)	−0.0920
Date	Fri, 13 Sep 2024	Log-likelihood	−82.755
Cov. Estimator	Unadjusted		

Variable	Coefficient	Std. Err.	T-stat	P-value	Lower CI	Upper CI
Temperature	0.0349	0.0093	3.77	0.0003	0.0165	0.0533
Precipitation	0.0002	0.0001	1.61	0.111	−0.00004	0.0004
Agriculture	0.0250	0.0558	0.45	0.655	−0.0859	0.1359
Industry	0.1055	0.0528	2.00	0.049	0.0006	0.2104
Services	0.1366	0.0344	3.98	0.0002	0.0680	0.2052

scalable and data-efficient way to understand climate risk. More importantly, it makes that understanding usable by those who need it most: policymakers, planners, and local officials working in environments where information is limited, but the stakes are high.

4 Model validation

4.1 Cluster analysis of agricultural yield and GDP per capita

Figure 1 shows how countries cluster when grouped by agricultural yield and GDP *per capita*. The clustering highlights three distinct groups, each with implications for climate resilience policy.

Countries in **Cluster 0** have both low income (GDP *per capita* below $1000) and low crop yields (under 2 tons per hectare). These countries are highly vulnerable: they lack both the economic resources and agricultural performance to absorb climate shocks. Their resilience is constrained not just by environmental factors, but by limited infrastructure, weak institutions, and low investment in adaptation systems. This group typically represents countries where policy support, climate finance, and capacity-building efforts are most urgently needed.

In contrast, **Cluster 1** includes countries with higher income and better yields. Here, average GDP *per capita* exceeds $1000, and yields are generally above 2 tons/ha. These countries have been more successful in building resilience, largely due to stronger economic diversification, better access to inputs and technologies, and functioning support systems. Their position in the cluster map reflects a higher capacity to adapt.

Cluster 2 includes countries with intermediate characteristics—either modest incomes but relatively decent yields, or higher incomes with underperforming yields. These mixed cases may be at a tipping point: well-targeted investments in technology or governance could move them toward higher resilience, while neglect could push them into deeper vulnerability.

This cluster analysis supports the broader conclusion that resilience is shaped by both climatic and economic factors. Countries with similar climate conditions may show different outcomes depending on their structural readiness and development pathways (Lemi and Hailu, 2019; Badiane and Makombe, 2014).

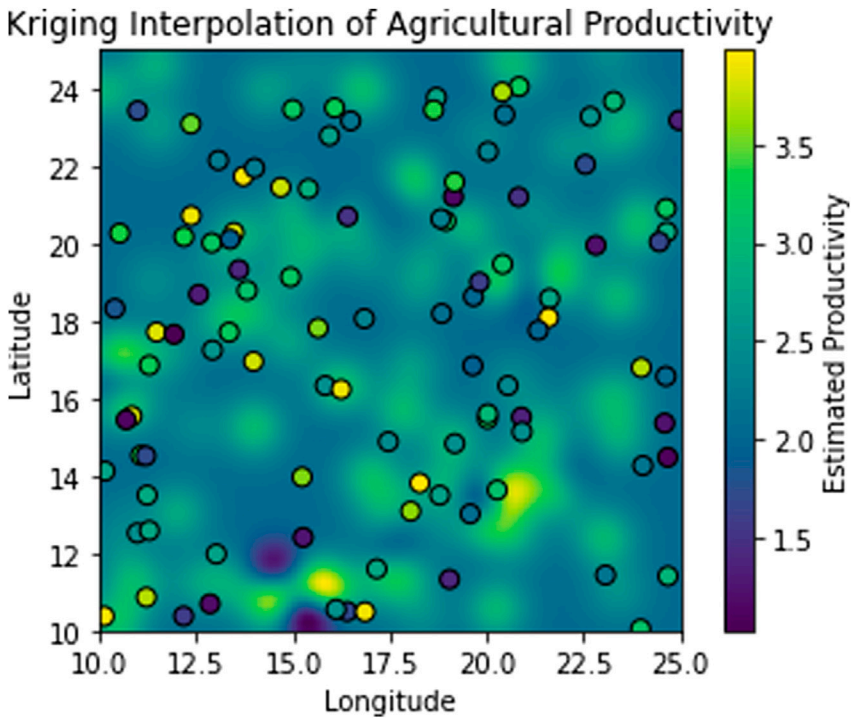


FIGURE 2
Kriging-based interpolation of agricultural productivity.

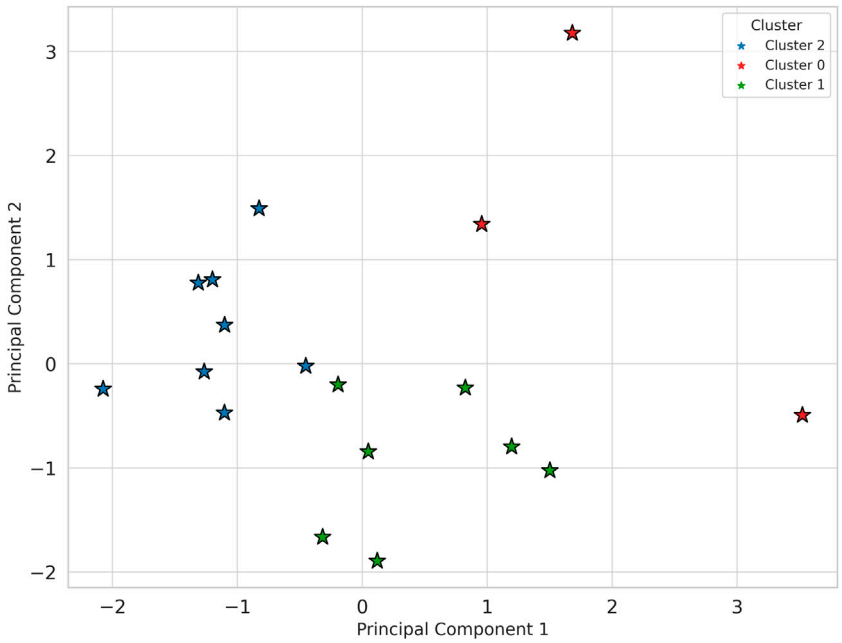


FIGURE 3
Cluster visualization of countries by resilience and structural variables.

4.2 PanelOLS estimation of agricultural yield

The regression results in Table 1 show how key factors affect agricultural yields across countries. While the overall model explains only a small portion of the variance (R-squared of 0.034), it still offers useful insights. The coefficient on precipitation is positive and nearly significant ($p = 0.094$), suggesting that rainfall plays an important role in shaping agricultural output, even if the relationship is not strongly linear. This aligns with existing studies emphasizing the yield-sensitivity of rainfed systems in LICs (Habib-Ur-Rahman et al., 2022; Raza et al., 2019). Temperature has a negative coefficient, as expected, though not statistically significant in this model. This suggests that heat stress may reduce yields, but the effect varies across contexts. In regions with better infrastructure or heat-tolerant crops, the impact may be partially offset. GDP *per capita* is positively signed but insignificant, reflecting the earlier cluster result, i.e., income matters, but its effect is mediated by how it is spent—whether on technology, access to markets, or policy support. Finally, the share of the labor force in agriculture appears to have no clear relationship with yield in this model, which may reflect structural inefficiencies in agricultural labor markets—where a large workforce does not necessarily translate to high productivity.

4.3 Kriging-based interpolation of agricultural productivity

Figure 2 presents a spatial interpolation of agricultural productivity using kriging, combining sparse ground-level data with satellite-derived climate variables. The resulting map illustrates how productivity varies significantly across geographic space—even within relatively small regions—and helps identify pockets of climatic and structural vulnerability. The map reveals areas of comparatively high productivity, typically clustered in zones with moderate rainfall, fertile soils, and better infrastructure such as roads and market access. In contrast, low-productivity zones are often found in more peripheral or arid regions, where poor soil quality, limited access to water, and infrastructural deficits constrain output. Some areas fall below 1.5 tons per hectare, highlighting chronic production challenges. This spatial approach is crucial for policy planning in low-income, data-scarce environments. It enables the identification of priority zones for targeted interventions—such as irrigation investment, infrastructure upgrades, or soil rehabilitation—without requiring exhaustive ground data. Additionally, high-performing regions can be analyzed for best practices and potentially scaled as models of climate resilience. By leveraging limited data with robust geostatistical methods, this tool offers a scalable, cost-effective approach to localized adaptation planning and resource allocation (Bussi et al., 2021; Costella et al., 2023).

4.4 Resilience model: Sector-level panel estimation

The model presented in Table 2 estimates sector-specific contributions to national climate resilience. The results show that both industry and services significantly improve resilience, while agriculture has a statistically weak effect. The strong result for services (coefficient = 0.137, $p = 0.0002$) suggests that economies with robust service sectors—education, health, financial services—are better positioned to absorb climate shocks. This reinforces the importance of economic diversification as a resilience strategy (Badiane and Makombe, 2014; Diao et al., 2018). Temperature is also positively associated with resilience, which may seem counterintuitive. However, it likely reflects adaptive responses—such as the adoption of heat-tolerant crops or shifts to more climate-resilient economic activities—especially in countries with adequate institutional support (Habib-Ur-Rahman et al., 2022). Precipitation, again, shows a weak but positive influence. Its low statistical significance highlights that rainfall alone does not determine resilience; what matters is how rainfall is managed—through irrigation, storage, or planning systems.

Figure 3 shows how countries cluster based on structural characteristics and resilience scores, using a PCA-based visualization for clarity. Each point represents a country, positioned along two principal components that summarize key indicators: GDP *per capita*, labor force distribution in agriculture, and the sectoral share of industry and services, alongside resilience estimates from our panel model. While PCA is used here solely for visual simplification, the clustering itself is grounded in actual structural metrics.

This clustering offers more than a statistical grouping—it reflects meaningful patterns in economic structure and adaptive capacity. Countries on the left side of the plot tend to have low industrial diversification and high dependence on agriculture, correlating with lower resilience scores. Those on the right typically combine higher GDP *per capita* with more balanced economic sectors, aligning with stronger resilience. These patterns emerge directly from the data, not assumptions, and offer a grounded way to compare countries based on both exposure and capacity.

This is especially important in contexts where high-resolution, time-series adaptation data are missing. Instead of analyzing resilience in isolation, this approach embeds it within broader economic context—helping avoid misinterpretation in structurally diverse regions. The method strengthens the study by offering a way to generalize resilience patterns across similar economies, even when detailed local data is unavailable.

For policymakers, this visualization supports strategic alignment and peer benchmarking. A country lacking full resilience data but falling into a well-defined cluster can still be assessed with reasonable confidence. More importantly, countries within the same cluster may share policy challenges and solutions. This opens the door for targeted peer learning, especially on institutional reforms, adaptation financing, or infrastructure planning.

In short, this clustering bridges the gap between abstract resilience scores and the economic realities that shape them. It enhances both the interpretability and practical utility of our approach—offering a scalable, structure-aware diagnostic tool for resilience analysis in data-scarce settings.

Figure 4 presents a heatmap of sector-specific climate resilience scores across five countries. It highlights how resilience varies not just across countries, but also across sectors—agriculture, industry, and services—within the same economy. This visual reinforces a

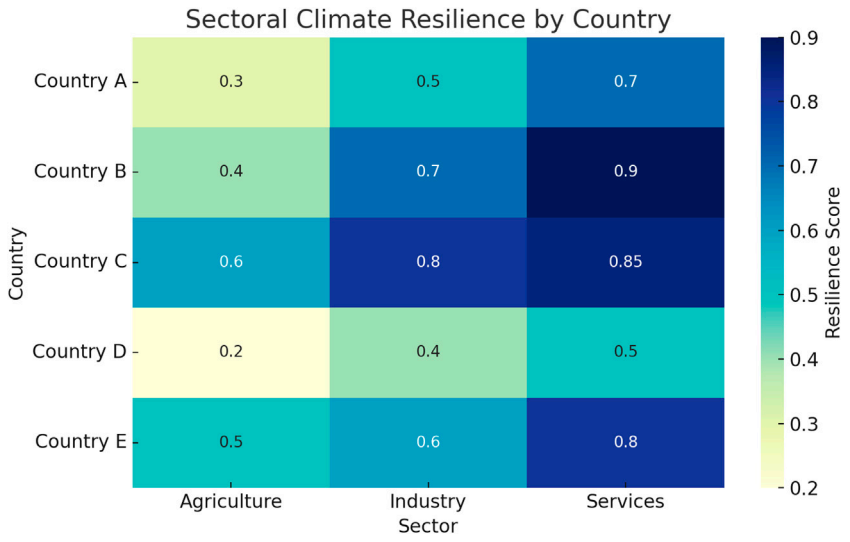


FIGURE 4
Sectoral climate resilience by country.

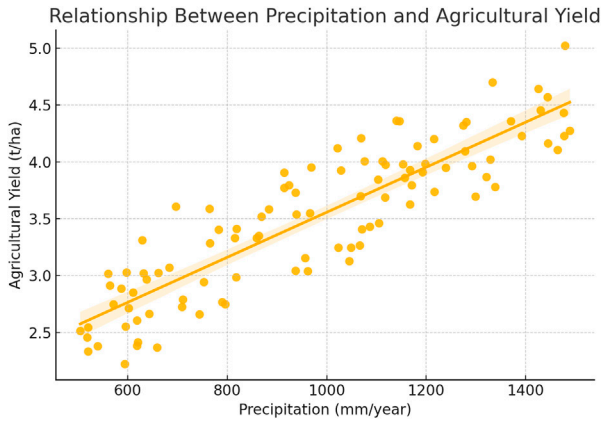


FIGURE 5
Kriging-based interpolation of agricultural productivity.

central argument of this study: that economic structure directly shapes resilience outcomes. The pattern is clear. Countries with higher resilience in services tend to show stronger overall resilience. In contrast, those with weak agricultural resilience often exhibit broader vulnerability. For example, a country with low resilience in both agriculture and industry reflects the risks of structural dependence on primary sectors without adequate adaptive systems. This insight is especially relevant for economies where agriculture remains dominant but under-supported.

The value of this heatmap goes beyond simple comparison. It serves as a diagnostic tool for both cross-country benchmarking and within-country targeting. Policymakers can use it to identify which sectors are lagging and whether resilience is evenly distributed. A country may show strong performance in one sector—such as services—while masking critical weaknesses in another. Without disaggregated visualizations like this, such imbalances are easily overlooked, especially when data are limited. More importantly, the heatmap supports targeted, sector-specific adaptation strategies. Many adaptation plans still treat climate resilience as a uniform challenge across sectors. This visualization shows why that approach fails. For instance, a country with strong service resilience but moderate agricultural performance may need to prioritize support for rural infrastructure, water access, or agricultural extension systems. Conversely, a country with consistently high scores across all sectors offers a potential structural model for economies still in transition.

This tool also has clear relevance for data-scarce contexts. Even when a country lacks full resilience estimates, patterns from structurally similar peers can serve as proxies for strategy. If one country shares sectoral characteristics with another but lacks local data, it can still make informed decisions based on available peer profiles. In sum, the sectoral heatmap advances our broader objective of localized, structure-aware resilience analysis. It improves the empirical foundation for sector-specific planning, provides a practical guide for prioritizing adaptation investments, and supports policy alignment across structurally similar economies. It demonstrates clearly that climate resilience cannot be understood or improved without first understanding the economic composition of the system being assessed.

This scatter plot shown in Figure 5 illustrates the relationship between annual precipitation and agricultural yield, revealing a broadly positive association between the two variables. As precipitation increases, agricultural productivity—measured in tons per hectare (t/ha)—tends to rise. While the strength of the correlation may vary across contexts, the visual trend line consistently affirms a key assumption underlying our empirical framework: that climatic inputs, particularly rainfall, play a direct and often dominant role in determining agricultural outcomes. Primarily, it supports the climate sensitivity assertion. The resilience of agricultural systems in many regions—especially in data-scarce, rainfed economies—hinges on climatic stability. By visually confirming that yields respond positively to rainfall, this

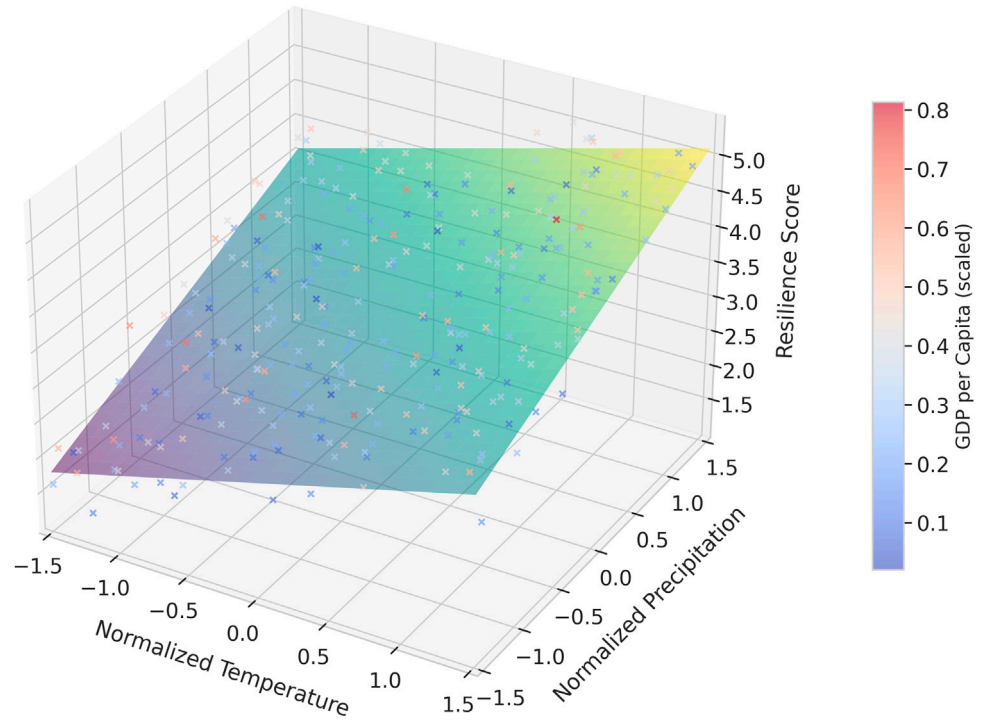


FIGURE 6
Resilience asymmetry surface.

figure validates the core mechanism of our panel yield model. It demonstrates that climate-linked variability in rainfall is not an abstract or theoretical risk, but a real and observable driver of yield outcomes. This strengthens the claim that any resilience framework must explicitly account for climatic sensitivity, particularly in agricultural systems that lack buffering infrastructure.

Figure 5 also provides a communicable, intuitive visualization of an otherwise technical econometric relationship. In policy or field contexts where technical regression tables may not be interpretable, this plot offers a more accessible depiction of yield vulnerability. It allows stakeholders, from planners to farmers, to see that yield shocks are not random but climate-explained, reinforcing the need for climate-informed agricultural planning. This makes the case for targeted investments in adaptation tools, such as irrigation systems, soil moisture conservation, or early-warning weather systems.

Technically, it also justifies the spatial and structural disaggregation embedded in our resilience mapping framework. The magnitude and form of this relationship will differ by location, crop, and economic structure, and the observed trend here underscores the rationale for localized intervention design. Where rainfall is erratic or declining, the consequences for yield—and thus for food security and rural livelihoods—can be severe. Visualizations like this one help prioritize high-risk zones for support, especially when formal data systems are incomplete or out of date.

In effect, this figure anchors the climate-agriculture nexus in observed reality, offering an empirical foothold for our broader resilience arguments. It helps translate econometric findings into strategic insights and strengthens the justification for integrating climate variables into agricultural policy, especially in fragile, rainfed settings.

Ultimately, this plot complements and reinforces the multi-layered logic of the paper: that understanding and improving climate resilience requires localized, sector-specific insights grounded in data—even where such data is sparse. By showing the observable dependency of yield on rainfall, the figure lends strong support to our call for structural resilience strategies that recognize climatic exposure as a first-order development constraint.

4.5 Resilience-Asymmetry Surface (RAS)

Figure 6 introduces the Resilience-Asymmetry Surface (RAS), a diagnostic tool developed to uncover hidden vulnerabilities and strengths in resilience outcomes. This surface maps resilience as a function of both climate conditions and economic capacity, offering a three-dimensional view of how these elements interact. The height of the surface represents predicted resilience, while the color shows GDP *per capita*. This visualization reveals several key insights. First, countries with moderate temperatures and rainfall—but higher

income—tend to sit at the peak of the surface, demonstrating strong adaptive capacity. Conversely, countries with similar climates but lower income lie at the bottom, showing weak resilience. This divergence points to a resilience asymmetry: even with similar environmental exposure, outcomes vary sharply based on structural economic conditions. These asymmetries are often hidden in traditional models, which average out responses across space and sectors. The RAS can help policymakers prioritize where structural improvements—such as improved governance, access to finance, or support for innovation—can yield large resilience gains. It also identifies outliers: countries performing worse (or better) than expected, given their climate and income levels. This offers valuable input for peer learning and cross-country collaboration. In settings with limited data, the RAS serves as a high-level but intuitive tool that helps narrow down where more detailed studies or interventions should focus. It also underscores a broader message of this paper: that climate resilience cannot be explained by climate exposure alone. Institutional, structural, and economic conditions play a central role—and must be considered in any serious policy response.

5 Analysis & discussion

The full set of validation results presented in this study, spanning econometric estimations, cluster diagnostics, spatial interpolation accuracy, and structural mapping tools—collectively strengthen the credibility, applicability, and novelty of our climate resilience framework. These results do not stand in isolation; taken together, they provide empirical grounding for the core claim of this paper, that is, climate resilience in low-income countries is best understood through a combined cross-country and localized lens, especially when working with limited data.

Input: Sparse agricultural data, satellite-derived climate data
Output: Spatial map of predicted productivity under climate stress
Step 1: Integrate spatial data
  Merge local agricultural observations with satellite climate data within a GIS framework.
Step 2: Model specification
  Estimate parameters in the model:
$$P(x,y) = \alpha + \beta_1 C(x,y) + \beta_2 Z(x,y) + u(x,y)$$
Step 3: Spatial interpolation
  Use kriging based on spatial correlation to predict $\hat{P}(x,y)$ across the entire domain.
Step 4: Visualization
  Map the predictions to identify spatial patterns of vulnerability and resilience.
Step 5: Output
  Deliver policy-ready maps indicating zones for intervention, investment, or monitoring.

Algorithm 1. Localized Climate-Agriculture Mapping.

The panel estimations and clustering exercises confirm that climate impacts are not evenly distributed across sectors or economies. More importantly, they show that meaningful structure exists in resilience patterns even across sparse, heterogeneous datasets. This justifies our use of harmonized panel methods for comparative insights, and validates the claim that resilience differences can be systematically identified—even in contexts where data gaps are substantial.

Spatial validation, especially through the kriging interpolation maps and associated diagnostics, demonstrates that actionable information can be extracted from incomplete field data. The models consistently recover localized yield patterns that align with environmental gradients and known structural constraints, suggesting not only internal validity but external relevance. The consistency across three distinct country cases further reinforces the robustness and portability of the approach. These validation results thus support a central premise of the study: that localized resilience analysis is both feasible and necessary, and can be built using open-source tools and sparse inputs.

The diagnostic surfaces—particularly the Resilience Asymmetry Surface—offer an added layer of interpretability that links statistical estimation with strategic planning. Its empirical grounding through validated model outputs lends confidence to its role as a policy-relevant heuristic, rather than a conceptual abstraction.

Therefore, our results have demonstrated that our methods are not just technically sound, but context-sensitive and operationally useful. They demonstrate that in data-scarce environments, rigorous modeling combined with targeted spatial methods can yield insights that are both statistically defensible and decision-ready.

6 Policy implications

The findings from this study offer several practical insights for policymakers seeking to improve climate resilience in data-constrained settings. Some of these include;

1. The use of structural data to inform sector-specific adaptation. The cross-country analysis shows that resilience varies significantly by sector, and that structural factors—such as labor distribution, industrial base, and access to services—are strong predictors of resilience outcomes. Countries with limited agricultural performance but strong service or industrial sectors tend to be more resilient. This suggests that national adaptation strategies should go beyond agriculture and support structural transformation as a long-term resilience measure (Badiane and Makombe, 2014; Diao et al., 2018).
2. Targetting subnational hotspots with localized interventions. The spatial productivity maps produced through kriging reveal where vulnerabilities are concentrated within countries. These maps can help governments prioritize investments in irrigation, extension services, or climate-smart infrastructure in low-performing regions, even when field data is limited. This is especially important for targeting resources efficiently, rather than applying uniform strategies across diverse regions (Bussi et al., 2021; Costella et al., 2023).
3. Combining economic data with climate models for smarter adaptation planning. The Resilience-Asymmetry Surface (RAS) shows that resilience is not simply a matter of climate severity. Some countries or regions face moderate

climate conditions but remain highly vulnerable due to weak economic foundations. Others perform well under stress due to economic or institutional strengths. This insight reinforces the importance of integrating socioeconomic diagnostics into national climate planning processes.

4. Focusing on resilience gaps, not just climate risk. RAS also identifies areas where resilience is unexpectedly low given the climate profile. These "resilience gaps" are often overlooked in conventional risk assessments that focus only on weather extremes. Policymakers should consider these gaps as missed opportunities—regions where relatively modest investment in capacity-building or infrastructure could lead to large gains in resilience.
5. Building with what is available. One of the central advantages of this approach is that it works with limited data. The methods used—panel econometrics, kriging, and satellite integration—are accessible, transparent, and replicable. LICs do not need to wait for perfect datasets or global models to begin planning. With basic field observations, publicly available climate data, and open-source tools, much can already be done.

These insights support a shift in how resilience is understood and planned for. Rather than framing resilience only in terms of risk reduction, this study encourages policymakers to also think in terms of opportunity—where better use of existing data and targeted action can produce large and lasting impacts.

7 Conclusion

This study presents a dual-level framework for analyzing climate resilience in low-income countries: a cross-country econometric model for sectoral resilience, and a localized mapping method for agricultural productivity using spatial interpolation. Together, these approaches provide a scalable, data-efficient way to identify both national-level patterns and subnational hotspots of vulnerability.

Our findings confirm that structural economic factors matter as much as climate exposure in shaping resilience. Countries with strong service and industrial sectors tend to be more resilient, while agriculture continues to underperform without targeted investment and adaptive support. The kriging-based approach allows high-resolution estimation of productivity even in data-poor regions, guiding spatially targeted adaptation strategies. Meanwhile, the Resilience Asymmetry Surface offers a diagnostic for understanding resilience gaps not visible in traditional risk assessments.

Overall, the tools and findings from this study support more grounded, equitable planning for climate adaptation. The framework is designed to work with the data that countries already have and can be extended as more information becomes available. It offers practical ways to support decision-making in environments where climate risk is urgent, but data are sparse.

Data availability statement

The datasets analysed in this study are available upon request, from the corresponding author.

Author contributions

RK: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review and editing.

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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.

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Livelihood adaptation to climate-related changes in agroecological zones in developing countries—challenges, prospects, and policy concerns

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Climate change significantly threatens the livelihoods, biodiversity, and food security within agroecological zones (AEZs) of developing countries. This research presents a systematic review of peer-reviewed articles published between 2013 and 2023, highlighting facilitators and deterrents of effective livelihood adaptation strategies across AEZs within developing nations. The study identified two main thematic areas from these studies across several geographic regions: Challenges and Policies. These thematic areas were common across the AEZs, each with four primary subthematic areas. These subthemes highlighted insufficient stakeholder engagement, inconsistent policies, environmental harm or damage, and technological deficiencies. The review highlights the urgency of incorporating traditional participatory approaches and enhancing stakeholder harmonisation for robust policy formation. It emphasises the need for a tailored approach to adaptation strategies to address the distinct social, ecological, and governance structures of each unique AEZ according to its geographic characteristics. Finally, this review offers a new perspective on the complexity of climate change adaptation in AEZs, while establishing the foundation for future scholarly work and policy initiatives pertinent to enhancing resilience and coping mechanisms to climate change within AEZs of developing nations.

KEYWORDS

agriculture, coping mechanisms, climate change, global warming, human activities

1 Introduction

Agroecological zones (AEZs) are distinct regions of land characterised by a unique combination of uniform agro-climate, ecology, soil types and agricultural practices [Food and Agriculture Organization of the United Nations (FAO), 1978]. AEZs have a critical role in food security in developing countries, where most of the population relies on smallholder farming and agriculture for their livelihood (Hossain et al., 2019). In recent decades, increased global temperatures and unstable climate conditions have amplified human-induced climatic impacts, affecting agricultural output and ecological balance (Abbass, 2023; Monaco, 2023). This has led to numerous uncertainties in the status quo and the management and adaptation

of agroecological zones (AEZs) (Aniah et al., 2019). The resultant effects in AEZs are heightened frequencies of extreme floods, droughts, and wildfires, variability in rainfall and temperature patterns, and threats to food systems and ecological sustainability (Mutunga, 2023). Developing countries are especially susceptible due to their low levels of technical capacity, fragile institutions, and resource scarcity (Umemiya et al., 2021).

In Pakistan, for example, temperatures are expected to rise, and rainfall variability will likely increase by 2050, leading to more flooding, droughts and heat stress events (Savelli et al., 2022). Recent studies have shown an almost one-third inconsistency in crop yield due to rising global temperatures, resulting in climatic variations or increased variability in rainfall and temperature patterns (Zvobgo et al., 2023). This means that if the climate becomes more variable, agricultural production and food security can be compromised (Aggarwal et al., 2018). Apart from the adverse impacts on food security, damages sustained by AEZs (an example in Bangladesh) due to extreme weather and climatic events have led to population displacement, loss of livelihoods and threats to biodiversity and ecological niches, which are needed to ensure a balanced AEZ (Jayawardhan, 2017). Adaptation measures are thus acutely necessary for livelihood security and sustainable development. The strategies are constantly obstructed by fractured policy frameworks, poor stakeholder participation, and local variability in AEZs (Dube et al., 2016; Seaman et al., 2014).

These issues have been acknowledged by the United Nations Framework Convention on Climate Change (UNFCCC) since 1994, which has recommended that developing countries receive the highest priority in receiving financial incentives for livelihood adaptation (Eriksen et al., 2021). Rural economies within developing countries, specifically those in Latin America, Asia, Africa and the Caribbean, have recently endured economic hardships due to the loss of livelihood stemming from disruptions in AEZs by climate change (Madzivhandila and Niyimbanira, 2020; Tiyo et al., 2015). According to Hoque et al. (2019), approximately 2.5 billion people in developing countries depend on AEZs for income and survival; thus, comprehending vulnerability and adopting robust adaptation strategies are essential. A Tey et al. (2017) review concluded that developing countries struggle to adopt and implement sustainable agricultural practices.

Despite the increasing volume of literature on climate change adaptation, several gaps have persisted. These include a shortage of region-focused policy analysis, a limited emphasis on participation in governance processes, and a shortage of Latin American and Caribbean AEZ representation. Further, a shortage of systematic thematic syntheses complicates policymakers' and practitioners' navigation through the landscape of adaptation.

This paper fills these gaps by systematically reviewing how policy interacts with challenges and livelihood adaptive strategies in AEZs. It provides a thematic analysis with a clear structure, classifying literature into logical sub-themes to improve the practical utility of findings. The purpose of this review is to: (i) consolidate adaptation issues and policy measures in AEZs in developing countries; (ii) derive regionally based shifts in adaptation strategies; and (iii) put forward actionable recommendations for consideration in future adaptation planning. The research is aimed at policymakers, agricultural planners, NGOs, and academic researchers engaged in climate adaptation.

1.1 Literature review

Several studies have examined the socio-economic aspects of climate adaptation in AEZS. For example, according to the Ricardian approach, Hossain et al. (2019) analyse the economic effect of climate change on crop cultivation in Bangladesh. The results indicate important regional variations in vulnerability. In a different study, flood risk behavior in Bangladeshi smallholder farmers evidenced a low willingness to pay for insurance and indicated a necessity for non-monetary adaptation measures (Hossain, 2024, 2025).

The same concerns are reflected in the literature on efficiency and credit rationing in Boro rice cultivation (Rabbany et al., 2021), where it was discovered that access to resources considerably affects adaptive capacity. Taken in concert, these studies emphasise the necessity of interventions tailored to context and point to the inadequacy of one-size-fits-all approaches".

2 Materials and methods

This study was done using a systematic review process outlined and combined by Filyushkina et al. (2016), Pullin and Stewart (2006), and Snyder (2019). Existing peer-reviewed literature provides a solid foundation for any investigative or research endeavour looking for gaps and limitations, irrespective of the study area. A systematic review entails gathering and comparing findings, more often studying and evaluating effects to apprise policy and application or practices (Snyder, 2019). A systematic review is most appropriate and beneficial when analysing and extracting critical data and information across a large body of literature (Liberati et al., 2009).

This review examines livelihood adaptation measures within AEZs in developing countries, focusing on policy limitations that hinder successful adaptation to climate change. The principal aim is to highlight the socio-economic and demographic insights of farming communities, the effectiveness of adaptation strategies and the most commonly adopted methodologies found in the literature.

2.1 Search strategy

The primary data repositories used in this review were online scientific journal databases for peer-reviewed articles, including Google Scholar, EBSCOhost, Jstor, Lexis Library, vLex, and Research4life/HINARI. Grey Literature was obtained from the University of Guyana and social media platforms like LinkedIn, ResearchGate, and Academia.edu. Searches were limited to peer-reviewed publications from 2013 to 2023. Groundbreaking or prominent publications before 2013 were included for foundational context.

Search Terms and Strings were combined keywords such as:

"Agriculture Zones, Agroecological Zones" OR "AEZs".

"Livelihood adaptation" OR "Climate Change Adaptation".

"Low-income countries," "developing countries" OR "Underdeveloped nations".

Searches were refined using Boolean operators. Filters were configured to obtain the required publication type (peer-reviewed articles, government reports and NGO reports) and language (English).

2.2 The inclusion criteria and exclusion criteria

2.2.1 Inclusion criteria

Studies that alluded to or addressed adaptation measures within AEZs in developing countries.

Studies that evaluated the impacts of adaptation on agricultural productivity, environmental sustainability, and economic resilience within AEZs. Empirical studies consist of quantitative, qualitative, or mixed-method designs that focus exclusively on AEZs within developing countries. Research focused on policy-driven, technological, and/or community-based interventions within AEZs of developing countries.

2.2.2 Exclusion criteria

Studies were excluded if they focused on AEZs within developed countries. Studies that focused on non-AEZs. Studies that focus solely on mitigation strategies. Studies were solely based on theoretical models without empirical evidence or data. Opinionated pieces, columns, editorials, and studies lacking peer review or scrutiny from the scientific community were also excluded.

These strict criteria for inclusion and exclusion ensured that the review concentrated on actionable strategies compatible with the distinct challenges present in AEZs of developing countries.

2.3 Screening and selection process

The screening of articles was executed in three stages. The first stage was "Title Screening," followed by "Abstract" and "Full-Text Screening." One screener executed Title Screening, while two independent screeners were responsible for the second and third stages, "Abstract" and "Full-text Screening." Abstracts were reviewed to assess their relevance to the study. The evaluation of full-text articles was also executed based on the inclusion criteria.

Humans did the entire screening process—blinded fields, such as the authors' and journals' names, were applied during screening to reduce bias. A Kappa statistical test was used to measure the level of agreement between speakers (Nichols et al., 2010). A value between 0.61 and 0.8 indicates substantial agreement, while a value of 0.81 and above indicates perfect agreement. When discrepancies were highlighted, discussion and consensus were used to resolve these. Duplicate entries were removed using the reference management software EndNote. Decisions from each screening round were documented in XLSX and CSV formats using Microsoft Excel.

Figure 1 shows the PRISMA flowchart, summarising the identification, screening and selection of studies for inclusion in this systematic review (Page et al., 2021).

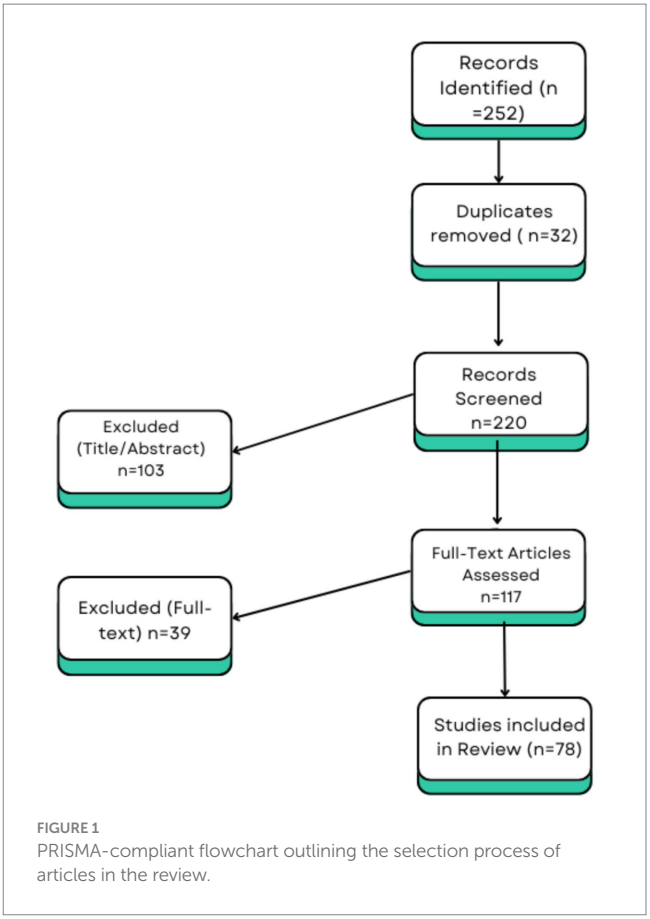


FIGURE 1
PRISMA-compliant flowchart outlining the selection process of articles in the review.

2.4 Quality assessment

Randomised and non-randomised studies evaluated the livelihood adaptation strategies in AEZs in developing countries. To reduce the risk of bias while ensuring methodological rigour, two tools were used:

1 The Cochrane Risk of Bias Tool (RoB 2.0), used with randomised controlled trials (RCTs) (Higgins et al., 2019)

2 ROBINS-1 [Risk of Bias Tool (RoB 2.0)] for non-randomised and observational studies (Sterne et al., 2016)

2.4.1 Application of the Cochrane risk of bias tool (RoB 2.0)

RCT used in this review evaluated interventions such as the impact of financial subsidies or policy interventions on agricultural productivity, testing the efficiency of irrigation systems and the introduction of crop-resilient varieties. The domains assessed were: (1) Randomisation (communities and farmers), ensuring these were randomly assigned to control groups and interventions. (2) Verification of Intended interventions (whether interventions were delivered and received as planned, and if deviations were documented correctly). (3) Measurement of Data from Outcome (Assessed whether results, e.g., crop yield, were consistently measured objectively across all participants). (4) Missing Data from Outcome (verification if missing data was handled appropriately, if outcomes were not reported from all participants). (5) Reported results (verified if all or selective outcomes were reported).

Each independent reviewer categorised studies as (a) having a low risk of bias, (b) having moderate concerns, or (c) having a high risk of bias. Any discrepancy was resolved through consensus among the moderators or arbitration involving a senior reviewer.

2.4.2 Application of ROBINS-1 (risk of bias tool (RoB 2.0) for non-randomised studies)

Most studies in the review focused on non-randomised real-world scenarios, e.g., assessing the impacts of changing climate

patterns on livelihoods and comparing adaptation strategies across different geographical localities or farming communities. The domains assessed were: (1) Confounding Bias (assessed whether studies controlled for parameters such as disposable income, education level or farm size that can potentially influence results). (2) Selection of participants (evaluated whether farmers or communities were self-identified and selected or systematically distinct amongst comparison groups or interventions). (3) Classification of interventions (verified if interventions were consistently applied and clearly defined). (4) Deviations from intended interventions, (5) Missing data, (6) Quantification or Measurement of Outcomes and finally, (7) Bias in the selections of the results reported.

The two independent reviewers categorised studies into the following categories of bias: (a) low, (b) moderate, (c) serious or (d) critical.

Studies with critical ratings were excluded unless a sensitivity test showed that such inclusions would not significantly skew the overall review's results.

2.5 Sensitivity analysis

The exclusion of High-risk or Critical-risk studies from the Cochrane Risk of Bias Tool (RoB 2.0) and ROBINS-1 assessments was validated via a sensitivity analysis. These studies were reintroduced in the synthesis process to evaluate their impact on the findings and conclusions. If consistency was observed, then the exclusion of these studies was justified.

2.6 Synthesis of data

2.6.1 Data extraction

The qualitative and quantitative variables were extracted during the data synthesis process.

2.6.1.1 Data extraction

The primary dependent variables extracted from studies were economic impacts, agricultural yield/production, and effects on the environment and the farming community. Descriptive statistics, including sample sizes, standard deviations, means and variances, were all accounted for.

2.6.2 Data synthesis

2.6.2.1 Synthesis blinding

This technique minimised bias. Two independent synthesists worked on the data synthesis. The authors' identities and other study features were concealed to ensure that all conclusions were data-driven.

2.6.2.2 Qualitative synthesis

This was achieved via thematic analysis. Emerging and recurring themes about adaptation strategies were identified and categorised. The synthesis of these themes achieved a comprehensive understanding of adaptation measures and their effectiveness.

2.6.2.3 Quantitative synthesis

Where applicable, statistical aggregation methods were used to synthesise quantitative data, allowing for understanding the impacts of adaptation strategies adopted across studies.

2.6.2.4 Reconciliation process

The independent syntheses were reconciled via coordinated dialogue and discussions. In the event of a disagreement, a senior reviewer was then consulted as a mediator to attain balance and accuracy in the synthesis phase.

2.7 Reproducibility

A systematic protocol was first developed and registered with the OSF Registries (Doi: 10.17605/OSF.IO/DAX56), Centre for Open Science, to ensure transparency and rigour of the methodology used in this review.

2.8 Limitation

The following limitations of this review include:

1 The exclusion of studies that were not available in English, which could potentially introduce a language bias in the review
2 The inconsistency in the quality of grey literature
3 The limited availability of quantitative data affected the statistical synthesis.

3 Results and discussion

The synthesis uncovered two global themes—Challenges and Policies—each with four main sub-themes presented in Figure 2 and explained in full detail in what follows. The themes were found in 78 studies reviewed across varied AEZs in Africa, Asia, Latin America, and the Caribbean.

After synthesising the peer-reviewed literature, two main thematic areas emerged: challenges and policies. These principal themes were central to addressing adaptation uncertainties within AEZs. According to Lourenço et al. (2014), adaptation uncertainties refer to the unpredictable nature of the effectiveness of adaptation measures adopted or implemented. These unpredictable outcomes pose significant risks to ecosystem sustainability and agricultural productivity (Luo et al., 2022). The challenges identified are directly a result of insufficient data, bureaucratic barriers and difficulties with implementing strategies. The policies cover innovative strategies and existing frameworks designed to amplify adaptation efforts. Minor cross-cutting themes are discussed in 3.1; while not embedded in Table 1, these are referenced to contextualise their part in addressing adaptation uncertainties.

The literature highlighted four (4) key areas where challenges presented themselves in livelihood adaptation in AEZs and four (4) principal policy concerns across all levels and categories of stakeholders, as seen in Figure 2. These challenges and policies varied according to the locality or geography of the AEZ studied. These



FIGURE 2
Occurrence of themes and sub-factors in the synthesised literature.

variations emphasised the urgency for nuanced approaches in each respective zone.

Challenges within the context of this review entail variables that present themselves within AEZs that directly affect the livelihood, causing degrees of uncertainty related to livelihood adaptation unless recommendations are swiftly implemented. Policy within the context of this review investigates administrative or political directives that must be streamlined for the sustainability of livelihoods and AEZs. The four (4) categories of challenges are as follows: (1) Environmental protection, in the context of this review, discusses how monitoring, security and the enforcement of regulations are crucial in the management and sustainability of AEZs. (2) Insufficient stakeholder engagement—addresses information sharing, correspondences, outreaches, partnerships and engagement amongst all participants or investors in AEZs. (3) Technology—adopting modern technology in agriculture and associated practices is highly costly (Gaffney et al., 2019). In this review, the challenges inherent in adopting technology allude to any instrument, hardware, or software and any methodological practice that must be adhered to successfully implement the desired adaptation measure in AEZs. (4) Planning relates to the challenges faced in successfully implementing livelihood adaptation strategies.

The four categories of Policy identified within the synthesised literature were as follows: (1) Sustainable agricultural practices – these policies required an extension services structure to assist farmers in implementing sustainable farming practices that consider both farmland and ecological health in the AEZ. (2) Land use policies – these were measures which directly spoke to land degradation in AEZs and how the absence of these institutional mechanisms affected the livelihood of farmers within AEZs. (3) Understanding Sensitivity – These policies highlighted within the literature referred to comprehending and addressing vulnerability, class and inequality amongst farmers, and (4) Political ideology-this spoke directly to the government agenda and was characterised by the philosophy of the government, aimed at shaping the culture of the society. Sustainable agriculture and land use planning were the most frequent policy instruments reported in the literature, with 15.2% of the studies sourced. Meanwhile, 8.9% of the policies addressed the lack of understanding of sensitivity in AEZs and provided prudent recommendations to address these gaps. Political ideology was the least evident theme of policies in the literature used in this study, comprising 3.8% of the articles synthesised (see Figures 2, 3).

3.1 Environmental protection challenges

A study in China used GIS and statistical analysis to highlight the rapid increase of ecological pressure due to human activities in AEZs, thereby threatening sustainable development (Zhang M. et al., 2022; Zhang X. et al., 2022). The results of the aforementioned study highlighted that more work is needed to prioritise environmental protection while balancing economic growth with ecological security. The diversity within the ecosystem is rapidly decreasing; species are directly threatened due to rapid urbanisation. This decline in species diversity challenges livelihood adaptation due to a significant reduction in crucial ecosystem services that farmers largely depend on. Kossebe et al. (2022) conducted a similar study in Cameroon and reported similar results to those mentioned above. The native *Adansonia digitata* (Baobab) tree in Cameroon, known for its diverse applications, is endangered, which can negatively impact the current and future generations of farmers within the AEZs. Industries are also negatively impacting the environment. A study by Tabe-Ojong et al. (2022) shows such impacts of the oil palm sector on the AEZs through soil erosion and degradation. Suggestions to improve the oil palm

TABLE 1 Articles and identified areas used in the review.

Key area identified	Geography	Representative authors and years
Challenges in environmental protection	Africa	Derbile et al. (2022), Kossebe et al. (2022), and Tabe-Ojong et al. (2022)
Challenges in environmental protection	Asia	Chen A. et al. (2022), Chen Y. et al. (2022), Gao et al. (2022), Liu et al. (2022), Zhang et al. (2007), Niu et al. (2023), Peng et al. (2017), Song et al. (2020), Ullah et al. (2019), Wang et al. (2021), Yao et al. (2022), Zhang M. et al. (2022), and Zhang X. et al. (2022)
Insufficient stakeholder engagement	Africa	Aidoo et al. (2021), Aniah et al. (2019), Antwi-Agyei et al. (2021), Kephe et al. (2020), Mihiretu et al. (2021), Tanimonure and Naziri (2021), and Tannor et al. (2022)
Insufficient stakeholder engagement	Asia	Chatterjee et al. (2021)
Insufficient stakeholder engagement	General	Lescourret et al. (2015) and Warner et al. (2022)
Insufficient stakeholder engagement	Latin America And The Caribbean	Fay Buckland and Campbell (2021)
Challenges in technology	Africa	Aliku and Oshunsanya (2018), Ibidhi and Ben Salem (2018), Lozano-Jaramillo et al. (2019), Maina et al. (2020), Musiyiwa et al. (2017), Uwizeyimana et al. (2018), and Wobeng et al. (2020)
Challenges in technology	Asia	Akhtar et al. (2022), Dey et al. (2020), Gupta and Mishra (2019), Mohapatra et al. (2021), Nabati et al. (2020), and Tian et al. (2014)
Challenges in planning	Africa	Enfors (2013) and Mugi-Ngenga et al. (2021)
Challenges in planning	Asia	Bapatla et al. (2022), Hossain et al. (2019), Zhang et al. (2020), and Muhammad et al. (2023)
Policy: sustainable agriculture	Africa	Besser et al. (2021), Dendir and Simane (2021), Kadiri et al. (2021), Ketema et al. (2021), Leauthaud et al. (2013), Ngetich et al. (2022), Rutebuka et al. (2019), and Zeleke et al. (2023)
Policy: sustainable agriculture	Asia	Basak et al. (2021), Dong et al. (2022), and Wang et al. (2022)
Policy: sustainable agriculture	General	Mrunalini et al. (2022)
Policy: land use planning	Africa	Tanougong and Tchamba (2022), Berihun et al. (2019), Mulualem et al. (2021), and Seo (2014)
Policy: land use planning	Asia	Chen et al. (2019), Devendra and Thomas (2002), Jiang et al. (2020), Malhotra et al. (2021), and Yan et al. (2020)
Policy: land use planning	Latin America And The Caribbean	Valverde-Arias et al. (2019)
Policy: land use planning	Global	Di Vittorio et al. (2016)
Policy: understanding sensitivity	Africa	Bonny et al. (2019), Mekonnen et al. (2019), Owusu et al. (2021), and Taye (2021)
Policy: understanding sensitivity	Asia	Jiang and Xu (2022), Lian et al. (2020), and Pandey and Bardsley (2015)
Policy: political ideology	General	Zhang et al. (2021) and Dunlap (2023)
Policy: political ideology	Latin America And The Caribbean	Féliz and ElisaMelón (2022)

sector for smallholder farmers while protecting the environment require better-quality farm inputs and a robust legal framework to define and protect land rights within AEZs. Without this legal framework, farmers' livelihoods and adaptive capacity in these areas could face ruin as the global impacts of human-induced climate change continue to surge. Challenges related to comprehending drivers of vegetation degradation require cooperative programs at various levels that identify the key influencing factors. Studies by Peng et al. (2017), Song et al. (2020), and Zhang et al. (2007) all highlight the challenges of protecting grasslands and nomadic culture, both crucial for ecological safety and sustainable farming in AEZs in China. Derbile et al. (2022) researched indigenous fruit trees (IFTs) using a mixed-methods approach in Ghana, where it was found that these IFTs were highly susceptible to excess rainfall, as well as below-average rainfall, leading to droughts, decreasing production yields and affecting the livelihoods of rural households' women in particular. Risk assessments, integrated approaches and monitoring are all essential in reducing vulnerability and building resilience in AEZs. The challenges are in satisfying the pre-requirements mentioned. Many developing countries lack the resources and studies to fulfil these objectives adequately. A key recommendation from the aforementioned study was the promotion of Environmental Change Adaptation Planning (ECAP) to conserve and propagate IFTs. A study by Chen A. et al. (2022) and Chen Y. et al. (2022) conducted on the composition of soil elements using statistical analysis found that the distribution of soil properties varied along changing environments, similar to the previously mentioned case. Ecological restoration in fragile zones is focused primarily on sensitive areas and environmental protection. However, challenges such as risk assessment, monitoring and integrated approaches still emerged to a lesser degree, according to Wang et al. (2021). Yao et al. (2022) demonstrated that the stage Slacks-Based Measure (SBM) Data Envelopment Analysis (DEA) SBM-DEA method can assess the ecological security in the Songnen-Sanjiang region in Northeast China from 2006 to 2019. However, the

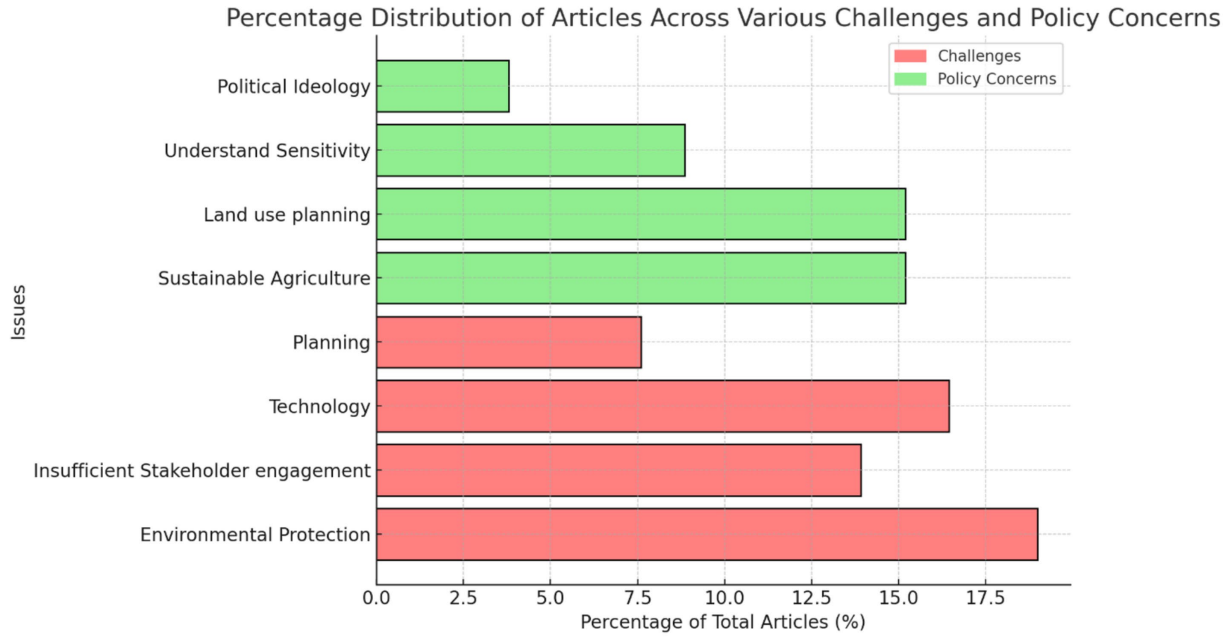


FIGURE 3
Percentage distribution of articles across issues highlighted.

certainty of these assessments depends on the accuracy of the model's input parameters. Without adequate ecological security, livelihoods face direct consequences; hence, the cautious interpretation of these results is emphasised.

Ecological security improved over time, and the Sanjiang Plains' environmental security was better than the Songnen Plain's. Again, in China, the important role of ecological engineering in promoting ecological restoration and the significant contribution of climate variability and change to net primary productivity (NPP) and soil retaining services were highlighted by Niu et al. (2023). The quality of the ecological data and the variability of the local environment determine the certainty of improvements in ecological security, contributions of ecological engineering and climate variability. This study helps address some of the challenges other regions face regarding ecological security. An increase in NPP would directly improve livelihoods, erosion prevention and nutrient and water retention, which are key factors that negatively impact AEZs. Another study by Gao et al. (2022) conducted in the karst area of Hechi, China, used a systematic approach to identify key ecological elements and prioritise areas for protection and restoration. However, the study alluded to the fact that as the socio-material needs of humans evolve, the uncertainty surrounding the benefits of projects geared towards environmental protection is becoming more evident. This presents a vivid challenge since livelihood adaptation would be more difficult to achieve. According to a study by Liu et al. (2022), sustainable agriculture and rural development can be achieved by harmonising energy development and ecological protection. This introduces a new paradigm, with challenges in developing environmentally friendly energy infrastructures in AEZs. Energy infrastructure impacts water resources via hydro plants and soil degradation via land use conversion. These challenges are comprehensive since agriculture relies on reliable energy to improve the efficacy in value-added processing, production and market access. Environmental protection is a prevalent challenge, but it is necessary to promote livelihood adaptation. As societies expand, more resources are consumed, increasing vulnerability and susceptibility. In Eurasia, Ullah et al. (2019) examined how human-natural systems have evolved in the Anthropocene, manipulating surface water and sediment dynamics to increase agricultural possibilities.

3.2 Challenges with stakeholder engagements

Communication, credibility, and knowledge awareness were hindrances to adopting climate services (Warner et al., 2022). The aforementioned study also highlighted inclusive and participatory approaches to stakeholder management as a transparent barrier to adopting sustainable practices through climate services. Kephe et al. (2020) also highlighted that climate change adaptation entails comprehending the present climatic conditions. Therefore, recommendations for better public-private partnerships and less bureaucracy to access financial aid must be prioritised. Mihiretu et al. (2021) looked at how Ethiopian agro-pastoral zone farmers perceived climate change and its origins, indicators, and impacts. The reasons, indicators, and impacts of climate change varied within different awareness groups. A lack of information and training was highlighted. A key recommendation was that better training and access to information can help farmers respond better to climate change. A Double Exposure Framework (adapted from Leichenko and O'Brien 2008) was used in rural Ghana to show that various factors, such as gender, occupation, location, and education, affect the perception of the effects on livelihoods. This study highlights a lack of farmer participation and empowerment among vulnerable groups. Tannor et al. (2022) concluded that the government and extractive industries

should provide alternate sources of income and better infrastructure to increase adaptation in AEZs.

The government should promote the marketing of underutilised Indigenous vegetables (UIVs) and non-government entities in Nigeria, and relevant material on climate change should be made available to farmers. Adopting agroforestry and perennial plantations should be considered (Tanimonure and Naziri, 2021). The aforementioned study highlights the use of a fundamental mechanism. However, challenges and limitations are evident due to farmers' level of consciousness and insufficient information on climate change shared by the stakeholders responsible. Antwi-Agyei et al. (2021) suggested that climate information should be more directly relevant to farmers' needs to improve usability and accessibility. A qualitative study in Ghana revealed barriers to increasing its uptake, such as inadequate information, low accessibility, illiteracy, and difficulties understanding technical language. There is a need for an exchange of knowledge between smallholder farmers and structural or accredited institutions to guarantee the sustainability of local adaptation measures (Aniah et al., 2019). The previous study explores smallholder farmers' reactions to climate and environmental variation in two rural Savanna areas of Ghana. Again, in Ghana, a qualitative study revealed that farmers employed 17 adaptation strategies, with the most common being the modification of planting days, variation of crops, use of resistant species of crop, and the monitoring of weather predictions via radio by Aidoo et al. (2021) as a means of successfully implementing livelihood adaptation in AEZs.

Knowledge of farming, household size, and insights about the impact and severity of human-induced climate change were all factors that affected the method planning in farming practices and livelihood adaptation strategies. Chatterjee et al. (2021) concluded that conservation agriculture (CA) is seen as a means to ensure food security and biodiversity preservation. However, unless the awareness levels of all stakeholders are heightened, conservation agriculture cannot be successfully implemented, which threatens the long-term viability of farming systems. Younger, more educated farmers were likelier to use climate services (Fay Buckland and Campbell, 2021). The results provided in this previous study highlighted ways to improve the architecture and delivery of climate services to increase resilience amongst stakeholders. General research was done by Lescourret et al. (2015) using conceptual modelling, it is asserted that Ecosystem-based, ES-based management has the potential to ensure the sustainability of agricultural systems. However, challenges exist where new stakeholders must take the lead to coordinate management efforts, and practical instruments must be identified and constructed for use by these groups. We have seen via the synthesised literature that insufficient stakeholder engagement in AEZs has presented several challenges across developing countries. In Africa, limitations mainly referenced infrastructural limitations in communication (Aidoo et al., 2021). In Asia, cultural barriers were more predominant, as highlighted by Kephe et al. (2020).

3.3 Technological challenges in AEZs

The literature synthesis alluded to challenges in soil fertility management, access to appropriate tools and machinery, pest and disease management, irrigation and water management. If farmers do not adequately adopt prudent technology measures, livelihood adaptation strategies such as technology adoption, prudent water management, diversification of farming practices, and information and knowledge applications cannot be successfully implemented.

Musiyiwa et al. (2017) investigated how farmers obtained information and insights on soil and water management technologies in different AEZs in Zimbabwe. Using a qualitative approach, it was found that soil and water management techniques matched farmers' preferences. This implied that farmers who unsuccessfully adopted methods in implementing the appropriate irrigation systems and maintaining soil health and fertility saw less yield or output.

Aliku and Oshunsanya (2018) illustrated that the SOILWAT model accurately forecasted maximum water retention, soil compaction, permanent wilting point, and soil saturation. They recommended incorporating organic material, salinity and silt modification to improve the model outputs. Access to technology, such as the SOILWAT model, is critical for wise soil fertility management in AEZs, especially when considering the variability in soil types and fertility levels across AEZs. Dey et al. (2020) looked at the impact of burning agricultural waste on soil characteristics, biological characteristics, and crop production in two different AEZs of India and Bhutan. Results show that using crop remains as raw straw and biochar can increase farming outputs by 36 to 64%. However, the challenge in this adoption method entails providing the technical support necessary for farmers to adopt alternative crop residue management successfully. Farmers who implemented the aforementioned technique saw increased soil quality and crop yield. Understanding the soil profile of AEZs increases the likelihood of successfully implementing practices that promote more robust soil fertility management.

Challenges in low organic carbon stock AEZs affect soil fertility, nutrient cycling, water retention, infiltration and resilience to extreme events. Wobeng et al. (2020) showed that soybean cultivation strongly increased microbial biomass and carbon use efficiency in the Guinean savannah. These findings suggest that soybean cultivation soil can be a sustainable approach to enhance soil microbial effectiveness and nutrient cycling in low organic carbon stock areas to improve fertility and resilience. Similarly, Maina et al. (2020) highlighted the possible role of organic modifications using statistical analysis, specifically cow manure, in controlling plant parasitic nematodes in maise-bean harvesting schemes, which are economically important crops for food security in Kenya. Cover cropping in many AEZs, as described by the previously mentioned studies, most often requires appropriate technological solutions, such as access to precision agriculture tools for optimising planting and soil health monitoring systems. However, the successful adoption of these approaches is often obstructed by barriers such as insufficient financial resources, access to technology, a deficit in technical expertise amongst farmers and substandard infrastructure in rural areas.

Information and knowledge dissemination are crucial to farmers in AEZs, but challenges in applying predictive models can hinder the delivery of crucial information. For example, using GIS and distribution models, Lozano-Jaramillo et al. (2019) highlighted the challenges of predicting which livestock breeds are best suited for specific environments. This is difficult because of the dependency on climatic parameters. If these parameters are misconfigured due to a lack of data or incorrect parameterisation schemes, the model's efficacy is compromised, potentially resulting in suboptimal livestock losses. Mohapatra et al. (2021) used machine learning techniques to predict seasonal groundwater levels in India and found that the Deep Neural Network model is the most effective, with an accuracy of 72.22%. However, the prediction ability is poor in certain regions due to data

availability, underscoring the need to strengthen groundwater monitoring networks and data acquisition systems. While predictive models hold great promise, their effectiveness is often restricted or limited by the availability and the quality of data, directly affecting their suitability for decision-making in AEZs. Akhtar et al. (2022) evaluated the Gravity Recovery and Climate Experiment (GRACE) to monitor changes in groundwater storage (GWS) in areas with limited groundwater monitoring systems. The correlation was poor in the mountainous region due to a delay of 4 months and limited observation wells. The complex terrain also caused inconsistencies in the connection due to variations in topography and subsurface characteristics. Therefore, caution should be exercised when interpreting GRACE's output in regions with varied geological and hydrological features since these factors influence groundwater assessments. These studies highlight challenges in data acquisition, which result in the underperformance of these technological applications designed to improve the sustainability of AEZs. Tian et al. (2014) proposed a joining outline among two extensively used crop simulations to enhance the micro foundation and effectiveness of the agroecological zone (AEZ) model. This framework consists of three steps: deriving, calibrating, and validating cultivar parameters, translating them into eco-physiological parameters, and applying the enhanced AEZ model. Another example by Gupta and Mishra (2019), a process-based crop simulation model was used to investigate the consequences of human-induced climate change on rice production in India by adopting AEZs instead of political boundaries.

According to the study, there is expected to be significant variability in different zones, and the changes in rice yield are expected to range from 2.9 to 17.8% in the 2080s. However, due to the geographical features of the study area, accurately calibrating the model was not without difficulties. The same hurdles can be faced if other AEZs with similar characteristics were to make use of this technology. Technology needs in AEZs vary significantly in terms of regions evaluated. Irrigation technologies and water usage were notably highlighted in arid regions, as also concretely suggested by Uwizeyimana et al. (2018). However, agricultural practices that build resilience to flooding are in demand in humid zones. Ibidhi and Ben Salem (2018) indicated that region-specific technological interventions must be considered to build the resilience of AEZs.

3.4 Planning and coordination challenges

Planning and coordination of activities in AEZs are interdependent due to increased climate variability. According to Muhammad et al. (2023), coordinating soil and climate conditions and planting challenges may negatively affect crop productivity. Hossain et al. (2019) and Zhang et al. (2020) forecasted that the impact varies by season and location as net crop revenues increase. Findings suggest that policymakers should consider specific AEZs when addressing the consequences of human-induced climatic change on crop agriculture. Seasonal variations pose challenges to farmers across different AEZs. Bapatla et al. (2022) highlighted the challenges of planning fertiliser applications by examining the impacts of surface air temperature on the Gram pod borer. This standard agricultural pest feeds on plants' protein biomolecules. Findings suggest that these predictions may help in planning and managing different zones of India, which promote adaptation and build resilience to temperature changes that are a consequence of human-induced climate change.

In Kenya, a study by Mugi-Ngenga et al. (2021) assessed how farmers use Indigenous knowledge in climatic prediction, their insights into climate variability, and adaptation plans. Challenges presented included integrating climate forecasting into farm planning activities. The study concluded that integrating Indigenous and conventional knowledge could be valuable for rain-fed-dependent smallholder farmers while planning for upcoming climatic seasons. Enfors (2013) investigated the ability of small-scale water system innovations (SWSIs) to increase productivity in farming systems. This type of transformation identified hurdles in planning and budgetary allocations available for integrating SWSIs in activities related to water resource management. The study concluded with recommendations for investment approaches to turn this potential into reality.

Without careful interventions in planning activities within AEZs across developing countries, the successful planning and execution of farming activities continue to be inhibited by challenges. Studies have shown that understanding climate variability is essential for developing robust agricultural strategies. Its relationship with crop yields and water availability is directly proportional (Challinor et al., 2014). Additionally, direct access to capital expenditure and financial resources is frequently highlighted as a key indicator of farming success in these zones (Kassie et al., 2015). Di Falco et al. (2011) observed that farmers with access to more capital were more likely to adopt climate-resilient strategies successfully. The aforementioned findings emphasise the need for targeted interventions supported by empirical evidence to improve livelihood adaptation in AEZs.

3.5 Policies for sustainable agriculture

The synthesised literature highlighted four principal policy concerns with varying applications across AEZs. The first policy highlighted in the literature is sustainable agricultural practices. Climate-smart agriculture has been identified as a key adaptation measure across AEZs. Mrunalini et al. (2022) highlight how legumes are highly suitable for climate-smart applications.

Besser et al. (2021) stated that restructuring farming systems to build resilience and adaptive capacity in AEZs emphasised the need for climate-smart agriculture and provided reasons why organisational and political efforts should be concerned about harmful environmental impacts from groundwater abstraction for agricultural purposes. Zeleke et al. (2023) have raised concerns about the effects on farmers' livelihoods and the sustainability of AEZs due to poor water quality from extracting deep, highly mineralised groundwater. Climate-resilient agricultural practices, if properly implemented, are necessary to decrease vulnerability. Similar studies related to climate-smart agriculture or climate-resilient practices highlighted concerns and the urgency to implement such policies related to water use and extraction done in Kenya by Malhotra et al. (2021). According to Wang et al. (2022) In Asia, soil erosion and its effects on farming are a concern, and a more integrated watershed management approach is needed. Population pressure was also found to result in stark contrasts between ecosystem service supply (ESS) and ecosystem social demands (ESD) of smallholder farmers, according to Ketema et al. (2021). Policies to address population growth, restore ESS, and improve SWB were all highlighted as practical measures in these AEZs. Ngetich et al. (2022)

also touched on the ESDs of smallholder farmers in Kenya since rainfed agriculture is vital in Kenya's arid and semi-arid zones. Enhancing livelihood adaptation can be achieved by combining scientific findings with local strategies to manage risks effectively in these AEZs.

Kadiri et al. (2021) studied the dynamics of Soil Organic Carbon (SOC) in arable land use in two AEZs in Nigeria. It was concluded that better soil management techniques improved SOC sequestration and soil fertility in the two AEZs, which can impact farmers' livelihoods. Climate and land use changes have weakened the interfaces among soil, plants, and grazing animals, reducing ecosystem services. Actions such as close-to-nature restoration and rotating grazing should be taken to recreate soil–plant–animal interfaces highlighted by Dong et al. (2022).

Dendir and Simane (2021) supported the implementation of all-inclusive policies concerning climate change adaptation strategies since variations in AEZs must be accounted for in order to implement livelihood adaptation successfully. Universally, the need for sustainable practices such as organic farming and crop rotation was recognised, but implementation can vary due to geography. In Asia, where drier regions are located, water harvesting and conservation are critical (Basak et al., 2021). Soil conservation, on the other hand, is a more pressing issue in Africa due to erosion caused by extreme climatic factors (Rutebuka et al., 2019).

3.6 Land use policies and their impact

Land allocation and zoning, restoration, conservation, ecosystem services, and infrastructure development are some of the few thematic areas highlighted across the literature synthesised. Tanougong and Tchamba (2022) demonstrated how climate change exacerbated the effects of forest cover loss via diversification, mainly for expanding AEZs, settlements, and livestock farming. Physical environments are critical in agriculture. Hence, farming practices vary widely based on these characteristics (Devendra and Thomas, 2002).

Land degradation results in losses and the inability to implement innovative adaptation measures against climate change's impacts, threatening farmers' sustainable livelihood. In some regions, ecological restoration projects are seen as a tangible solution to the issue of land degradation. Vegetation dynamics are highly related to climate change and its associated impacts on AEZs. Hence, understanding climate change projections is pivotal for successful land use policies. Di Vittorio et al. (2016) corroborate these findings by stating that results from projected future climate change data and historical climate data yielded different results. It was found that the uncertainty related to land demarcation should be measured. Therefore, biophysical and geopolitical factors are also important when modelling land change dynamics, as they provide the necessary evidence for appropriate land use policies.

These policies are very relevant as changes in land use patterns and livelihoods have significantly impacted traditional food systems in India. An example can be seen where the transition from traditional farming to commercial agriculture practices resulted in a decline in crop diversity and the migration of indigenous food sources. Malhotra et al. (2021) recommended reevaluating current tribal development practices in India, emphasising the need for more holistic socio-ecological approaches that integrate traditional knowledge and protect biodiversity while promoting agroecological farming. These approaches involve participatory land management that bolsters sustainable livelihoods, which align with the ecological and cultural needs of tribal populations. Yan et al. (2020) also examined the social and organisational changes in land use patterns and ecology, population relocation, land policy modifications, and social organisation reformations responsible for ecological degradation, affecting farmers' livelihoods. For example, Mulualem et al. (2021) demonstrate how various land uses and administration practices impact soil nutrient outflows in Ethiopia. Nutrient losses varied among AEZs, land use techniques and management practices, with cropland indicating the most losses compared to other types. However, management practices effectively reduced nutrient losses, mainly from water erosion. The variation of AEZs has been seen to show recurring concerns in how land use policies are crafted. Valverde-Arias et al. (2019) demonstrated significant differences in the environmental conditions between the two AEZs in Ecuador. These differences could impact the accuracy of Index-based Insurance (IBI). The IBI is a tool used primarily by smallholder farmers in developing countries to transfer risk. Essentially, it provides a degree of livelihood adaptation in these AEZs. Therefore, the land use policies cannot afford to neglect the key physical characteristics of AEZs, such as soil type, climatic features and topography. Governments should offer strategies and support to help farmers create a sustainable living landscape (Chen et al., 2019). The high-impact agricultural expansion was observed in forested areas in Asia by Jiang et al. (2020), Chen A. et al. (2022), and Chen Y. et al. (2022), which would require more robust frameworks. In Africa, however, according to Berihun et al. (2019) and Seo (2014), overuse of agricultural land is more prevalent, resulting in land degradation.

3.7 Understanding sensitivity in AEZs

A more profound comprehension of risk assessment and management allows policymakers to develop more appropriate strategies in AEZs (Thornton and Herrero, 2014; Gbetibouo and Ringler, 2009). Local development interventions should be based on the level of sensitivity according to Taye (2021), interventions should be based on the level of sensitivity. Climatic factors such as rainfall and temperature influence the differentiation of the populations (Bonny et al., 2019). Jiang and Xu (2022) studied how extreme climate affects vegetation in Northern China's Agro-pastoral Transition Zone. As in the prior study, temperature and precipitation mainly affected the Normalised Vegetative Index. The variation in hydrological variables and vegetation indices in AEZs is affected by rainfall (Lian et al., 2020).

Some AEZs may be more sensitive to two parameters: temperature and rainfall. This sensitivity to climate change and variability impacts crop yield, consequently affecting livelihoods. This implies the necessity for policymakers to take these concerns seriously. Vulnerable farming households are severely affected by AEZs. Mekonnen et al. (2019) also presented irrefutable evidence of the susceptibility of households and AEZs to climate change and environmental degradation. The adaptive capacity of households was the most significant factor influencing vulnerability, notably in the Ethiopian Highlands, and higher exposure in midland AEZs, for example, in central Ethiopia. The poorest households, commonly located in

lowland areas, accompanied by low livelihood diversity, were identified as highly vulnerable.

A study in Nepal found that the region's social ecosystems are highly susceptible to climate change. Substantial exposure and sensitivity to extreme weather events also limit adaptive capacity (Pandey and Bardsley, 2015). A key recommendation is to adopt an adaptation policy that addresses the most vulnerable households before expanding the reduction of social ecosystems nationally. The susceptibility of AEZs is proportional to the degree of environmental stressors or disturbances they face. Economic support mechanisms must be the key policy directive of areas with high poverty rates. In contrast, innovation and dissemination of knowledge should be prioritised in more technologically advanced regions Owusu et al. (2021).

3.8 The role of political ideologies in adaptation

Governance structures, economic systems, and universal policies contribute to crafting adaptation strategies. Various policy approaches have been the subject of concern and criticism across the studies. Féliz and ElisaMelón (2022) found that capitalism has a significant role in today's human-induced global climate crisis due to its emphasis on free market exploration of resources. Similarly, communist ideology has caused a need for concern relating to environmental sustainability. Large-scale projects, such as the Belt and Road Initiative (BRI), according to Zhang et al. (2021), traverse areas with fragile ecosystems that are highly susceptible to the adverse effects of human-induced climate change. Agriculture trade, investment, and infrastructure development can impact livelihood adaptation in AEZs. However, there is a gap in the literature that alludes to the BRI's environmental impacts. More research is recommended so that the impacts and environmental changes due to the BRI can be better comprehended in BRI environments and ensure future sustainability in these regions.

The green economy framework is often touted as a more sustainable approach by Governments worldwide. Dunlap (2023) argues that the green economy prohibits cohesive self-reflection and actions to recover ecosystems and address systemic socio-ecological issues adequately. The aforementioned policies highlight the complexity of adaptation strategies, which, apart from political ideologies, are also heavily influenced by the broader political, environmental, and economic landscapes. The efficacy of adaptation policies varies between geographical regions. This effectiveness relies heavily on economic conditions, governance, and international cooperation and relations.

3.9 Final thoughts and synthesis of key themes

A notable gap is highlighted in the comprehensive assessment of region-specific adaptation strategies, which evaluates their long-term robustness. It is also noted that very few of these studies analyse the contextual factors that ultimately determine the success or failure of adaptation strategies. There is a need for a more granular analysis of how these measures can be tailored to local contexts, specifically where AEZs in developing countries differ in climatic conditions, ecology, and socio-economic conditions. Broad generalised solutions are primarily found in the body of literature synthesised, often neglecting the crucial role of key socio-economic indicators: cultural norms, the level of education, social capital, and financial readiness. These aforementioned factors directly affect the adaptability and sustainability of adaptive strategies.

Also, this study shows a need for longitudinal studies assessing the long-term impacts of adaptive measures, which question the integrity and sustainability of adaptation interventions over time. Unexplored factors, such as the intersection of climate change with other concerns, such as market volatility, land tenure insecurity, and political instability, remain largely unexplored in existing research. In regions of high vulnerability, where smallholder farming communities are located in Asia, Africa, Latin America, and the Caribbean, this gap is notably evident, where a scarcity of available resources suppresses the adaptive capacity of AEZs. Identifying and addressing these implications are pivotal in developing tailored, region-specific policies that account for the social, economic and diversified environments and enhancing the resilience of AEZs.

These thematic trends are consistent with South Asian and West African studies. Hossain et al. (2019), Basak et al. (2021), and Dube et al. (2016), for example, in Bangladesh and Sahel countries, reported the enduring barriers to stakeholder disconnection, insufficient financial channels, and technological deficits. These findings affirm the cross-region applicability of the problems and policy shortcomings outlined in this review but highlight context-specific adaptation strategy approaches.

4 Conclusion and recommendations

This systematic review of peer-reviewed literature explicitly focuses on livelihood adaptation strategies adopted by agroecological zones (AEZs) in developing countries. Two main thematic areas were identified that hinder the smooth and effective adoption of livelihood adaptation strategies to climate change within AEZs. Those two thematic areas were Challenges and Policies. Challenges included environmental protection, technology constraints, and insufficient stakeholder engagement and planning. Policies comprise Sustainable Agriculture, Land-use Planning, Understanding Sensitivity and Political Ideologies.

The consolidation and analysis of 78 studies within the review presents a novel framework that expounds the dynamics of constraints and enablers of livelihood adaptation. More importantly, it emphasises the urgency of tailoring these policies to the social, ecological, and governance frameworks of each unique AEZ, considering its geographical and cultural characteristics. Thereby migrating from a broad-brush or generic approach to implementing livelihood adaptation strategies.

5 Key contributions

A new classification of adaptation hindrances and policy gaps across AEZs

1. The stratified geographical analysis includes Africa, Asia, Latin America and the Caribbean Regions
2. The acknowledgement of how understudied themes, such as how political ideologies and stakeholder awareness work in implementing adaptation strategies.

6 Policy implications

- Adaptation strategies should integrate contemporary methods and traditional knowledge to increase farming communities' resilience.
- Participatory planning should be emphasised in policy formation, especially in areas with low adaptive capacity.
- Private-public partnerships and communication on climate services must be improved to bridge critical stakeholder gaps.

7 Recommendations

1. Environmental protection: the application of Environmental Change Adaptation Planning (ECAP) must be enhanced and complemented by ecosystem-based practices.
2. Stakeholder engagement: multi-level governance systems can promote collaboration, trust, and information sharing.
3. Technology adoption: farmers should be afforded access to predictive modelling tools, and the investment in data acquisition systems should be prioritised.
4. Planning: planning frameworks should incorporate indigenous knowledge systems.
5. Policy support: the implementation of region-specific policies regarding sustainable agriculture and land use, following the distinct sensitivities of AEZs
6. Governance reform: establish strong institutions to monitor the impacts of large-scale development and ensure that policies comply with green economic frameworks.

8 Future directions

Future studies should incorporate the following:

- Enhance the inclusion of marginalised regions like Latin America and the Caribbean
- Cross-cutting concerns should be thoroughly assessed, such as political instability and the insecurity of land tenures
- Strong methodologies should be established to evaluate the long-term impacts of adaptation strategies.

Author contributions

EH: Investigation, Software, Conceptualization, Writing – original draft, Resources, Funding acquisition, Writing – review & editing, Visualization, Data curation, Validation, Formal analysis, Methodology. TO: Project administration, Supervision, Validation, Methodology, Funding acquisition, Conceptualization, Investigation, Resources, Writing – review & editing. EC: Conceptualization, Visualization, Supervision, Writing – review & editing. SM: Conceptualization, Writing – review & editing, Investigation, Data curation.

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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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Co-benefits of resilience planning: a review of analysis tools and methods

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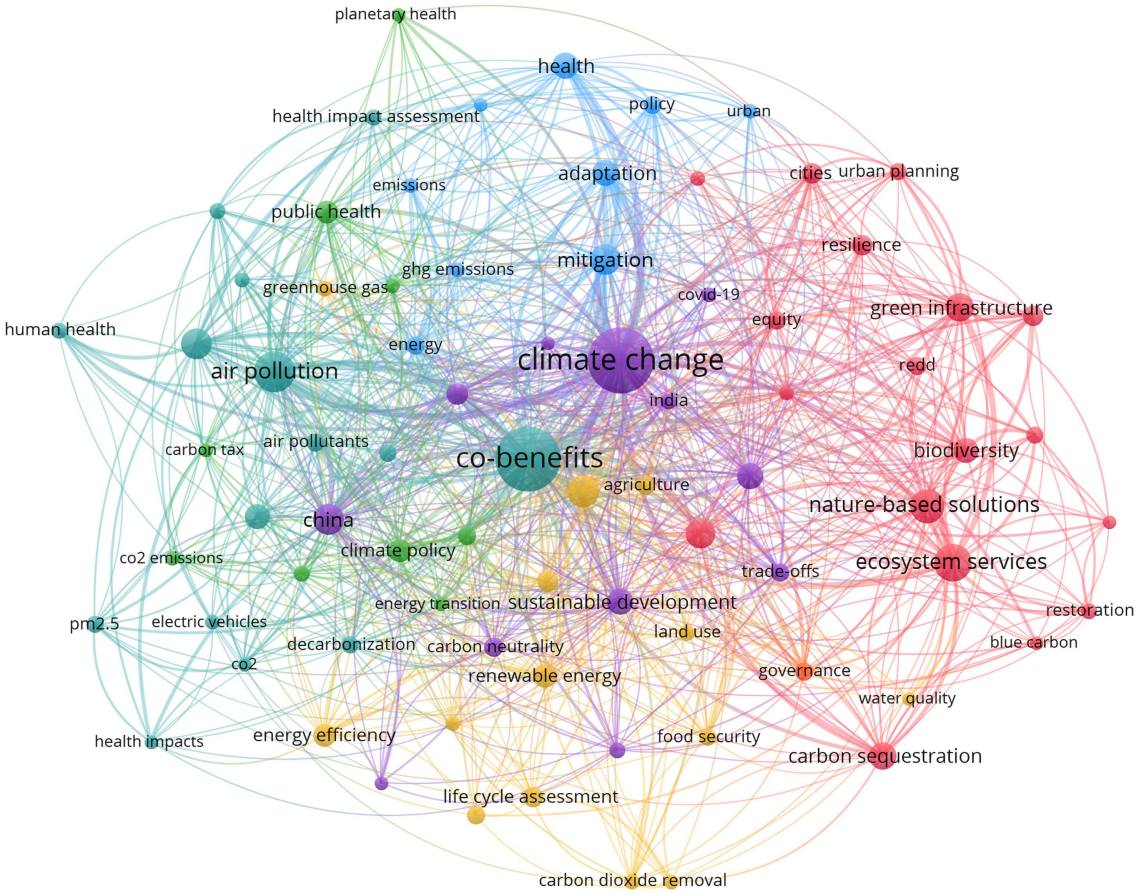
Co-benefits conceptually apply broadly to the realms of sustainability and resilience and are increasingly relevant in decision-making processes as there is an increase in complex and compound events. Therefore, infrastructure design, planning, governance, and disaster preparedness for compound events are critical for building resilient systems. Decisions are often based on direct benefits of a proposed project or intervention, which are the more salient to decision makers and may be the function of available financing and experience with event types. The ideal community resilience actions for a community may be heavily influenced by the identification (and inclusion) of co-benefits in assessments of community resilience alternatives. Fung and Helgeson reviewed the literature on co-benefits with a specific focus on the definition of co-benefits, areas where co-benefits are used the most (considering the literature related to climate change), and co-benefit measurement and assessment methodologies in the context of resilience planning. The current study further explores these areas by focusing on the development of the literature on co-benefits published since 2017. The specific review questions explored are: (1) What is the major focus of the literature on co-benefits? and (2) What are methods and tools for measurement and assessment of co-benefits? The literature review reveals two primary focus areas: co-benefits of resilience and sustainability planning, and co-benefits of climate mitigation and adaptation actions. The latter are further categorized as falling as either health co-benefits or environmental and social co-benefits of climate actions. Within the two broad focus areas, our study reviews research objectives, analysis region, co-benefit categories, direct benefits, and evaluation methods and assessment frameworks. Moreover, we provide a synthesis of analysis tools and assessment methods including monetization methods, multi-criteria (i.e., multi-objective) analysis methods, scoring methods and matrices, and systematic reviews. The review reveals several gaps and opportunities for both future research and applications. One opportunity is to develop more generic evaluation methods for co-benefits with a focus on scoring methods and matrices, which provide a good balance of quantitative and qualitative evaluation, in the development of more generic analysis and assessment methods and tools.

KEYWORDS

adaptation, co-benefit, resilience dividend, community resilience, co-benefits analysis

1 Introduction

Climate change is increasing the chances of multiple climate hazards occurring simultaneously or consecutively across the United States and its territories. Such interactions between multiple hazards across space or time, known as compound events, exacerbate the societal and ecosystem impacts of individual hazards and hinder the ability of communities,



GRAPHICAL ABSTRACT
Co-occurrence of keywords, identified in the corpus analyzed focused on co-benefits since 2017. There are six clusters of keywords identified. The first cluster, shown in red, contains 18 keywords with a focus (higher frequency of keywords) of climate mitigation, eco-system services, nature-based solutions, green infrastructure, and resilience. The second cluster, shown in green, has 15 keywords, with the most influential keywords being air pollution and air quality co-benefits. The third cluster, shown in darker blue, has 14 keywords with the most influential keywords being sustainability and renewable energy. The fourth cluster shown, in orange, contains 12 keywords with the most influential keywords being climate change, health co-benefits, and sustainable development goals. Clusters 6 and 7, shown in purple and lighter blue, respectively, each have nine keywords, with the most influential ones being climate policy, adaptation, and mitigation.

particularly frontline communities, to respond and cope. Therefore, infrastructure design, planning, governance, and disaster preparedness for compound events are critical for building resilient systems. Decisions are often based on direct benefits of a proposed project or intervention, which are the more salient to decision makers and may be the function of available financing and experience with event types. Building a business case can help determine the ideal community resilience actions for a community and may be heavily influenced by the identification (and inclusion) of co-benefits in assessments of community resilience alternatives.

The resilience dividend is a concept that has gained traction over the last decade as there has been an increase in the study and application of community resilience planning. The resilience dividend, defined as "the net co-benefit (or co-cost) of investing in enhanced resilience, in the absence of a disruptive incident" (Fung and Helgeson, 2017) is critical in the socioeconomic evaluation of community resilience alternatives. Creation of a business case for investment in community resilience planning strategies is often necessary to gain support for capital expenses associated with such efforts (Fung et al., 2021). Furthermore, the concept of co-benefits has been broadly adopted and extended to consider additional formulations, such as the resilience windfall (Helgeson and O'Fallon, 2021). Co-benefits conceptually apply broadly to the realms of sustainability and resilience and are increasingly relevant in decision-making processes as there is an increase in complex and compound events. Fung and Helgeson (2017) note that the definitions of co-benefits fall into three broad categories: objective-based, intent-based, and externality-based. We follow the broad definition of co-benefits introduced by the IPCC (2014): "effects that a policy or measure aimed at one objective might have on other objectives, irrespective of the net effect on overall social welfare."

There have been many definitions of co-benefits employed and the current paper builds upon the review and definition of co-benefits provided in Fung and Helgeson (2017). The current study focuses on the development of the literature on co-benefits, specifically reviewing documents that have been published since 2017 and related to environmental sustainability and climate and extreme weather event resilience. This is important, as societal losses from extreme weather and climate events have been increasing since at least the 1960s and continue to do so (Smith, 2021). In the period 1980–2023 there were 376 events that each cost $1 billion or more for a total loss of $2.707 T, with 66 of

those (or 17.5% of the events) occurring in the last three years (2021–2023) accounting for $438B in losses (or 16% of the total) (NOAA, 2024). The causes of these increases in losses are likely due to multiple factors, including climate change impacts that are amplified by increased development and encroachment into areas more vulnerable to natural hazards, as well as local (and in some cases global) increases in the rate of hazard events (Cutter et al., 2008; Mohleji and Pielke, 2014).

The scientific background of this study is grounded in the increasing integration of resilience planning and sustainability assessment within environmental and resource management fields. Co-benefits—defined as secondary or ancillary benefits that arise from interventions primarily aimed at other objectives—have gained prominence as climate-related shocks, such as floods and droughts, become more frequent and complex. In the context of water resource management, numerous studies (e.g., Lama and Chirico, 2020; Pirone et al., 2024; Errico et al., 2019) demonstrate how infrastructural and ecological interventions, such as vegetated channels, reservoir configuration, or green infrastructure, yield multiple hydrological, ecological, and societal outcomes. However, the valuation and comparison of such benefits—along with their trade-offs—remain challenging without robust, adaptable assessment tools.

This complexity underscores the importance of sensitivity analysis in both scientific and practical applications of co-benefit evaluation. In water systems, small variations in vegetation density, channel geometry, or reservoir outlet configuration can lead to disproportionate changes in flow resistance, peak discharge, and downstream flood risk—as demonstrated in the hydrodynamic studies cited above. Similarly, in resilience planning, the relative contribution of different co-benefits (e.g., air quality, economic revitalization, public health) may shift dramatically depending on the scale of intervention, stakeholder priorities, or assumptions built into modeling tools. Therefore, any assessment framework used in monitoring or managing natural resources—particularly those aimed at resilience and climate adaptation—must include methods to test the sensitivity of outcomes to input assumptions. Doing so enables more transparent, robust decision-making and enhances the credibility of proposed interventions in multi-objective contexts.

This paper is organized as follows. Research methods and materials are explained in Section 2. The associated bibliographic analysis results are presented in Section 3; information about content analysis of literature is presented in Section 4; and Subsection 4.3 is dedicated to co-benefits assessment framework and tools. Section 5 discusses and summarizes the important findings of this paper and major gaps in the literature. Finally, Section 6 discusses future research needs.

2 Materials and methods

In this study, we performed a bibliographic and content analysis of literature focused on the co-benefits of resilience planning. This study builds on the NIST Technical Note 1959 "Defining the Resilience Dividend: Accounting for Co-benefits of Resilience Planning," which defines a resilience dividend as "the net co-benefit (or co-cost) of investing in enhanced resilience, in the absence of a disruptive incident" (Fung and Helgeson, 2017). Fung and Helgeson (2017) reviewed the literature on co-benefits with a specific focus on the definition of co-benefits, areas where co-benefits are used the most (considering the literature related to climate change), and co-benefit measurement and assessment methodologies in the context of resilience planning. The current study further explores these areas by focusing on the development of the literature on co-benefits published since 2017.

The specific review questions we address are:

(1) What is the major focus of the literature?; and
(2) What are methods and tools for measurement and assessment of co-benefits?

The literature reviewed for this paper was drawn from both the Web of Science and Google Scholar. The Web of Science was selected because it covers all important and influential sources related to the topic of interest (Birkle et al., 2020). In addition, the article export format provided by Web of Science allows better bibliographic analysis using VOSviewer (Van Eck and Waltman, 2010). VOSviewer is a tool for constructing and visualizing bibliometric networks and text mining (Van Eck and Waltman, 2011). This software can be used to develop maps based on the input documents to show the focus of the literature and highly influential countries, journals, and authors.

The systematic review protocol included terms related to co-benefits and other alternative and/or related terms that are used in this research area. The specific terms searched on the Web of Science included "co-benefit[s]," "resilience dividend[s]," "ancillary benefit[s]," "co-benefits assessment tool[s]," "co-benefits gap[s]," "co-benefits definition," "co-benefits analysis," and "co-impacts." The focus of this study is on documents published since 2017, with the search date selected to include studies published between Jan 1st, 2017 and April 23rd, 2024. Using the search terms, 3,073 papers were collected from the Web of Science (WOS). Their full record, including title, author names, abstracts, keywords, and cited references, were exported to be used for bibliographic analysis in VOSviewer.

For the full content analysis and discussion, paper of relevance to the research questions were selected from WOS and Google Scholar. Collectively, 38 studies that were published after 2017 have been selected and reviewed in detail. The content of the final set of documents is analyzed in detail, and information that is of importance regarding the focus of the current study is extracted and presented in the form of tables. The tables provide information about the main objective of these papers, the region of study, suggested definition for co-benefit, assessment methods or tools for co-benefits, and primary and secondary objectives. Figure 1 provides an illustrative summary of the study framework.

3 Bibliometric analysis

To illustrate the evolution of the literature over time, the number of publications per year from 2010[1] to the present, is displayed in Figure 2. The results are based on documents found on WOS using the search terms mentioned in Section 2, using studies published between Jan 1st, 2010 and April 23rd, 2024 (Figure 2). The number of

1 The reference time to show the number of publications has been selected as 2010 (as opposed to 2017 which is the beginning of the time span considered in this paper for further content analysis) to better illustrate the significant increasing trend.

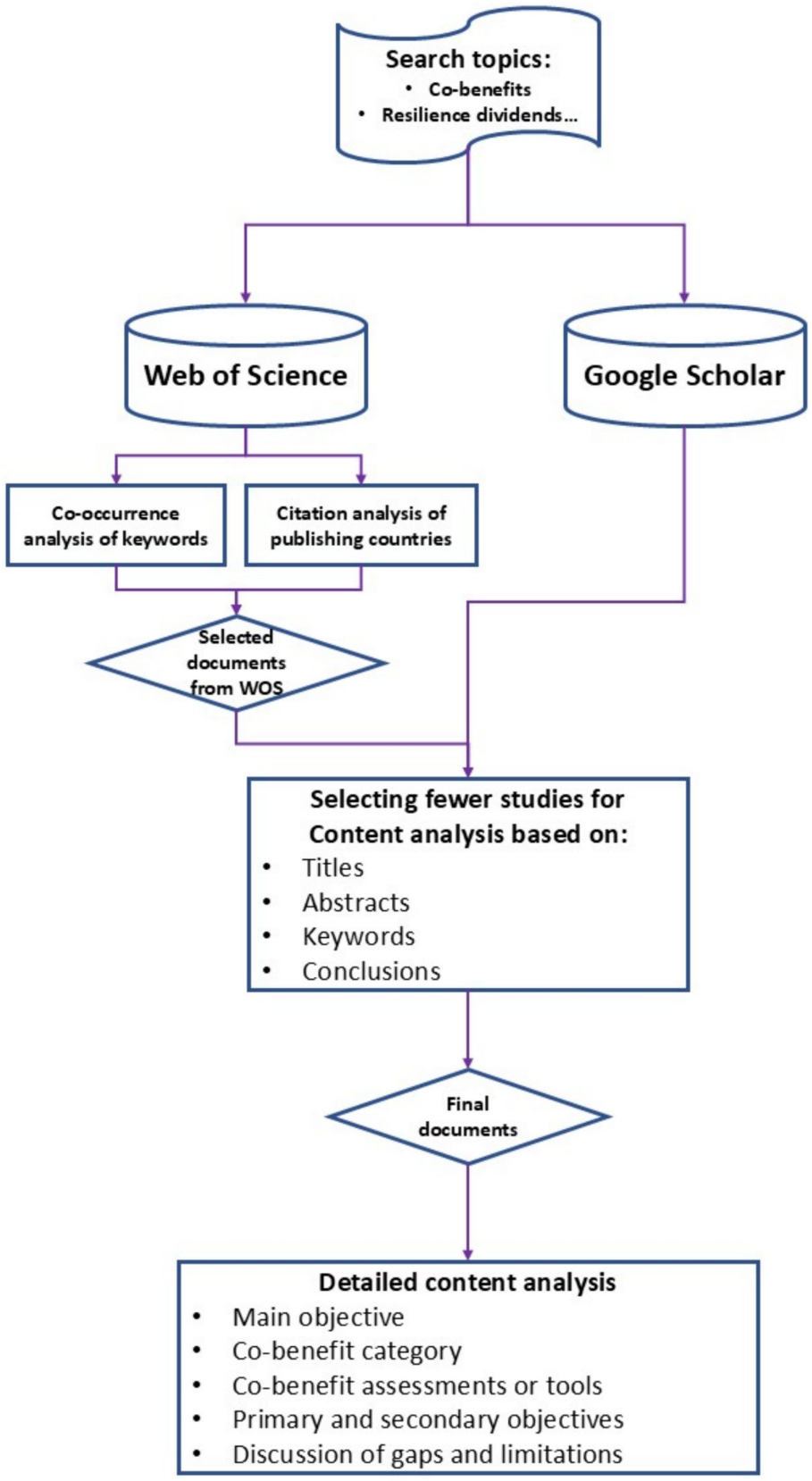


FIGURE 1
Study framework.

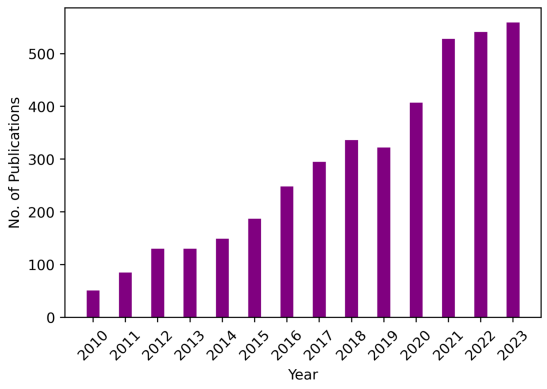


FIGURE 2
Number of publications per year.

papers published each year demonstrates an upward trend that emphasizes the importance of co-benefit topics across sectoral foci.

Bibliographic analysis was performed using VOSviewer. Two types of maps were created: (1) a co-occurrence map, which shows the foci of the selected literature based on the frequency of keywords, and (2) a map of highly influential countries that have published papers.

The co-occurrence map of keywords is based on studies published since 2017, found via the search terms discussed in Section 2 with a minimum occurrence of 15. Using this threshold, 78 of 7,761 keywords meet the requirement. A larger node size is consistent with a keyword with a higher frequency. The items or nodes are connected through links which shows the connection or relation between two items. Since the current map is based on co-occurrence of the keywords, a link represents whether two keywords have co-occurred in studies. Additionally, there can only be one link between any pair of items. Each link has a strength, denoted by a positive numerical value with greater values showing a more robust connection between a pair of keywords. For the co-occurrence map, a link with higher strength value means the number of publications in which two terms occur together is higher.

There are six clusters of keywords identified. The first cluster, shown in red, contains 18 keywords with a focus (higher frequency of keywords) of climate mitigation, eco-system services, nature-based solutions, green infrastructure, and resilience. The second cluster, shown in green, has 15 keywords, with the most influential keywords being air pollution and air quality co-benefits. The third cluster, shown in darker blue, has 14 keywords with the most influential keywords being sustainability and renewable energy. The fourth cluster, shown in orange, contains 12 keywords with the most influential keywords being climate change, health co-benefits, and sustainable development goals. Clusters 6 and 7, shown in purple and lighter blue, respectively, each have 9 keywords, with the most influential ones being climate policy, and adaptation and mitigation, respectively.

Based on foci demonstrated by the co-occurrence map, and in line with the study of Fung and Helgeson (2017), the co-benefits literature is categorized into two main groups: (1) co-benefits of resilience planning and sustainability and (2) co-benefits associated with climate change mitigation and adaptation actions. The second group is further categorized into two subgroups of health co-benefits of climate change actions, and environmental and social co-benefits of climate change actions. Detailed content analysis of the selected studies under these categories are presented in the next section.

Figure 3 demonstrates the most influential countries performing research concerning co-benefits since 2017. The map presented in Figure 3 is obtained from bibliographic coupling analysis which is defined as two documents that both cite the same document (Van Eck and Waltman, 2011). The minimum number of studies for a country to be considered in this analysis is set at 20. The bigger nodes represent countries with a higher number of studies. The US and China have the highest number of publications in this area followed by European countries (e.g., England, Germany, and Netherlands), Asian countries (e.g., Japan, India), and Australia.

4 Content analysis: overview of the literature

The studies included in the detailed review cover the general breadth of literature with an effort made to prioritize studies that provide an evaluation framework or an assessment method for co-benefits. These frameworks and assessment methods are discussed in detail in subsection 4.3. Tables 1, 2 summarize essential information for each study with respect to co-benefits of resilience planning and sustainability (Table 1) and co-benefits of climate actions (Table 2). The tables facilitate comparison between studies with respect to several factors, including the study's region of analysis, the main objective, the category of co-benefits, the evaluation framework or assessment tool, direct benefits, and co-benefits.

4.1 Co-benefits of resilience planning and sustainability

In this section, we provide an overview of studies focused on co-benefits of resilience planning and sustainability. This category is comprised of studies that explore resilience measures to select nature-based solutions (NBS) or green, blue, and gray interventions, monetize co-benefits associated with such measures, analyze synergies and disconnects between resilience and sustainability, and link resilience measures and indicators to Sustainable Development Goals (SDGs), the concept of resilience dividends, and disaster risk reduction. Most studies in this area implemented case studies to explore the impacts of considering co-benefits in economic analyses of resilience and sustainability investments. The methods to assess co-benefits include monetization methods, multi-criteria (i.e., multi-objective) analysis methods, and scoring methods and matrices. More detailed information on tools to assess and evaluate co-benefits is provided in subsections 4.3.1, 4.3.2, 4.3.3, and 4.3.4.

Studies have shown that quantifying the co-benefits associated with resilience and sustainability investments significantly enhances the economic viability and business cases associated with investments (Fung et al., 2021; Helgeson and O'Rear, 2018). In this context, the co-benefit is considered as the result of avoided losses in the presence and absence of disaster events, and co-benefits considering exogenous positive shocks pre-and post-resilience enhancing investments (Fung et al., 2021). Additionally, the concept of resilience windfalls has been introduced as "an unexpected or sudden gain or advantage of resilience planning" and can also be thought of as "the discrepancy

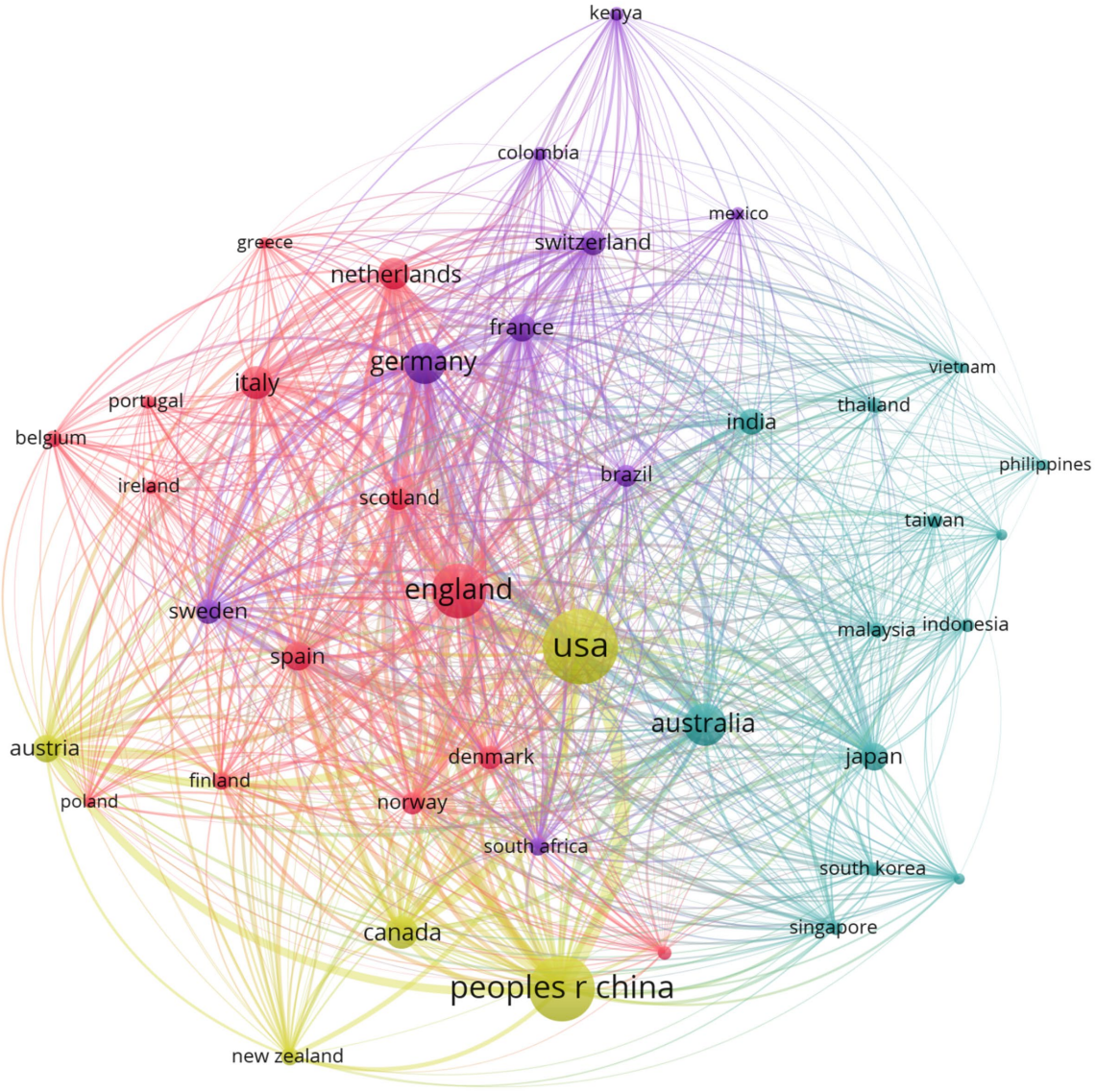


FIGURE 3
Highly influential countries in publication related to co-benefits.

between expected and actual avoided losses." The resilience dividends and windfalls provide a framework to expand the evaluation of resilience planning alternatives beyond simply avoided losses and may help justify resilience planning for a given community through the value of resilience planning for additional objectives. Informing a robust discussion around co-benefits and associated categories of resilience dividends and windfalls can help motivate increased learning and cooperation and effectively advance projects that address both resilience and sustainability (Helgeson and O'Fallon, 2021).

Exploring the synergies and discord across resilience planning and sustainability programs and the link that maps these two objectives to each other has been the focus of some of the reviewed studies. Understanding how synergies and differences in sustainability and resilience are encoded and implemented within a holistic framework, together with early design performance assessment, is an essential component in the operationalization of sustainability and resilience (Mirhosseini et al., 2019). Accounting for trade-offs like privacy, cybersecurity, infrastructure costs, and social biases in planning and implementation of SDGs in addition to co-benefits is crucial for ensuring effective contribution to sustainable and resilient urban development (Sharifi et al., 2024).

In assessment of co-benefits, it has been emphasized that the impacts of Disaster Risk Reduction (DRR) investments change in a non-monotonic ways, which requires a constant long-term evaluation through dynamic simulation and consideration of multiple resilience dividends (e.g., additional economic, social, and ecological benefits) can enhance the attractiveness of DRR efforts (Rözer et al., 2023; Yokomatsu et al., 2023). In addition to co-benefit assessment, the importance of co-impact assessment has been emphasized. Co-impact assessment aims to identify co-benefits and adverse side effects. In the case of climate change actions, they are usually associated with co-impacts in different sectors, and identifying them is a prerequisite to developing optimum policy packages. Co-impact assessment can lay out the knowledge base to

TABLE 1 Summaries of studies selected for detailed content analysis with regards to co-benefits of resilience planning and sustainability.

Reference	Region	Study's main objective	Category of co-benefits	Evaluation framework or assessment tool	Direct benefit	Co-benefits
Meerow and Newell (2017)	Detroit, USA	Introducing a spatial planning approach to identify tradeoffs and synergies associated with ecosystem services provided by green infrastructure, and to identify priority areas where green infrastructure can be strategically placed to leverage co-benefits	Environmental: Co-benefits associated with the use of green infrastructure	Introduced a Green Infrastructure Spatial Planning (GISP) model that leverages GIS-based multi-criteria evaluation of six benefit criteria including stormwater management, social vulnerability, access to green space, air quality, urban heat island, and landscape connectivity and expert stakeholder-driven weighting. The purpose of the suggested method is strategic placing of green infrastructure to maximize the co-benefits of planned green infrastructure.	Ecosystem services provided by green infrastructure, enhancing urban sustainability and resilience	Stormwater management, social vulnerability, green space, air quality, urban heat island amelioration, landscape connectivity
Helgeson and O'Rear (2018)	Maryland, USA	Highlighting the impacts of considering resilience benefits in economic analyses of residential sustainability investments	Environmental and Economic: Co-benefits associated with using a rooftop solar photovoltaic (PV) system	Life cycle costing (LLC) analysis	Solar-plus-storage from an installed rooftop solar PV system	Co-benefits that arise from sustainability planning (avoided damages and losses from avoided grid outages)
Keefe (2018)	USA	Analyzing the perception of social, economic, and environmental co-benefits as reported by communities through the HUD NDRC competition BCAs.	Social, Economic, Environmental and Natural Hazard: social, economic, and environmental co-benefits of resilience planning by communities in the HUD NDRC competition	Presented a methodology to analyze the NRDC BCAs. They created a table referred to as "The BCA crosswalk" to summarize the results from the NDRC BCAs. They developed codes-short phrases-to consolidate and represent the various types of co-benefits reported by applicants and the codes were used in the BCA crosswalk.	The World bank, triple dividend concept was used. Avoiding losses when disasters strike.	Unlocking development potential by stimulating economic activity thanks to reduced disaster related investment risks; and, social, environmental, and economic co-benefits associated with investments.
Alves et al. (2018)	Marbella (Spain), Ayutthaya and Sukhumvit (Thailand),	Presenting a multi-criteria approach for selection of green and grey infrastructure to reduce flood risk and increase co-benefits	Environmental: Co-benefits associated with the use of green and gray infrastructure	Proposed a method for selection of flood mitigation measures in urban areas based on a multi-criteria analysis that considers flood risk reduction, cost minimization and enhancement of co-benefits. The method comprises of several steps including screening (e.g., elimination of not applicable measures according to flood type), scoring (e.g., measuring performance assessment to enhance co-benefits), weighting (e.g., local preferences regarding co-benefits), and ranking (e.g., final scores calculation and ranking).	Flood risk reduction	Water quality, environmental (e.g., air quality, ground water recharge), liveability (e.g., urban heat reduction), economic (e.g., energy savings), socio-cultural (e.g., recreational uses)

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TABLE 1 (Continued)

Reference	Region	Study's main objective	Category of co-benefits	Evaluation framework or assessment tool	Direct benefit	Co-benefits
Alves et al. (2019)	Sint Maarten, Netherlands	Presenting a method to include the monetary analysis of co-benefits associated with green, blue and gray into a cost-benefits analysis of flood risk mitigation measures	Environmental: Co-benefits associated with green, blue and gray infrastructure used for reducing flood risk	The multi criteria method for measures selection proposed by Alves et al. (2018) is used to identify locally relevant benefits and the applicable measures to achieve these benefits. The green, blue, and grey measures are ranked based on the decision makers' analysis. Using the ranking, various combinations of measures are further analyzed, and a final set of measures and their associated benefits are selected which will be economically evaluated. The economic valuation is based on the relation between impacts on the environment and the consequent human welfare and usually estimated based on local data (e.g., instance energy and water prices).	Flood risk reduction	Co-benefits associated with green-blue infrastructure such as green roofs: energy savings, reduction of carbon dioxide (CO2) pervious pavements: heat stress reduction, energy saving, reduction of air pollutants, reducing surface temperatures up to 4°C.
Mirhosseini et al. (2019)	USA	Proposing a framework for describing the synergies and discords that occur between several 'resilience' and 'sustainability' building certification programs (BCP)	Environmental: Co-benefits and tradeoffs with regards to resilience & sustainability certification programs for climate change	Developed a matrix showing the relationships between multiple green building rating systems and resilience rating systems that is used to incorporate the interpretations of resilience cited in their paper. This comparison includes the rating system origin, application, and range of implementation as it considers resilience scholarship. The table aims to identify the problems, objectives, and co-benefits of various green building rating criteria and resilience criteria	Hazard mitigation, disaster resilience, vulnerability reduction, generally increase resilience and sustainability	Co-benefits associated with different certification programs, for example co-benefits of working toward increased energy conservation and energy efficiency

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TABLE 1 (Continued)

Reference	Region	Study's main objective	Category of co-benefits	Evaluation framework or assessment tool	Direct benefit	Co-benefits
Paunga and Lassa (2020)	222 countries and territories worldwide	Developing a global scale baseline of investment in disaster risk reduction worldwide	Environmental and Natural Hazard: Co-benefits of planning for natural hazard risk reduction (natural disasters are considered generally)	Presented an assessment framework for disaster risk reduction that included aggregation of investment in indicators of financial investment (foreign investment, development assistant, GDP, insurance penetration), social investment (access to education, health and water, and sanitation), early warning system investment (internet access, mobile phone access, public awareness, disaster monitoring, risk assessment), enabling environment (easiness of doing business, government effectiveness, the rule of law, corruption control, DRR budget allocation commitment)	Disaster risk reduction using measures of saving lives and avoiding losses	Unlocking development potentials by stimulating economic activity by reducing disaster-related investment risks. The third dividend relates to the co-benefits of DRR investment. These co-benefits include economic, social, and environmental co-benefits such as improved social cohesion, better environmental quality, reduced vulnerability to poverty.
Kurth et al. (2020)	USA (Coastal areas)	Exploring the challenge of quantifying the resilience benefits of coastal projects and developing an assessment method suited to existing projects and discussing ways forward to meet the challenges.	Environmental and Natural Hazard: Co-benefits of resilience planning for hazards associated with coastal zones (i.e., energetic storms and inundation by rising sea levels)	Developed a scoring system to evaluate the resilience co-benefits. They first categorized the engineering strategies that were implemented by each project and summarized them to 27 feature types. Then the feature type was evaluated for its contribution to 12 resilience indicators and 10 USACE business line indicators. Feature types received a binary 0–1 score for each indicator.	Environmental, economic, and social benefits that are generated by USACE projects.	Co-benefit associated with increasing interest in the USACE and other organizations in resilience (derived from EWN projects.)
Fung et al. (2021)	Cedar Rapids, USA	Developing a CGE model to quantify the net co-benefits of investing in increased resilience	Social, Economic, Environmental: Co-benefits associated with investing in increased resilience against natural hazards such as flood	Developed a CGE model to quantify the co-benefits at a high level, and to show how co-benefits are distributed throughout an economy. To calculate the co-benefits, the avoided losses is first quantified under a simulated flooding event for the 2007 time period. Then the economic co-benefits considering exogenous positive shocks, in the absence of a natural disaster for both time periods (pre-and post-resilience) are quantified.	Increased resilience to flood	Avoided losses from the investments in increased resilience (avoided employment and income loss) in an event of natural disaster, economic co-benefits due to neighbourhood revitalization in the absence of a natural disaster

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TABLE 1 (Continued)

Reference	Region	Study's main objective	Category of co-benefits	Evaluation framework or assessment tool	Direct benefit	Co-benefits
Helgeson and O'Fallon (2021)	Port Orford, and Portland Oregon, Alaska, American Samoa	Reviewing the use of co-benefits and the resilience dividend and introducing the concept of a resilience windfall	Environmental, Natural Hazard: Co-benefits associated with disaster resilience and sustainable planning	Through introducing the concept of resilience dividend and windfall, a framework is provided to evaluate the resilience planning alternatives that can assign value to the options. Multiple narrative examples are then used to explore the proposed framework which vary by locations, hazard types, and resilience intervention types to demonstrate the power of narrative exposition to communicate the importance of co-benefits.	Benefits associated with resilience and sustainability activities such as limiting GHG emissions or imposing caps on emissions	Co-benefits of resilience and sustainability measures related to human health or improvements to air quality
Cohen et al. (2021)	Multiple locations worldwide (Rwanda, Morocco, Japan, Marshall Islands, Chile, Lebanon)	Exploring the relationships between climate change mitigation action and co-impacts and the Sustainable Development Goals (SDGs) and illustrating it using a selection of examples from countries' Nationally Determined Contributions (NDCs).	Environmental: Co-benefits and tradeoffs of climate change mitigation actions.	Provided examples of co-benefits and adverse side effects and examples of SDG indicators that could be used to track progress, linked to different mitigation actions. Different types of co-impacts were considered including co-impacts in climate resilience and energy security. Investment and growth, employment, (biodiversity ecosystem services, soil), water pollution, air pollution, energy access, poverty alleviation, food and water security, health, Noise, congestion and other considerations that contribute to quality of life	Benefits of GHG mitigation actions in different sectors such as energy, industry, buildings, and waste	Co-benefits/ adaptation benefits has been mentioned for different mitigation actions. For example, for solar street lighting, co-benefits include Reduced reliance on grid-based power generation and infrastructure and imported energy. This has been linked to SDG 1, SDG 7, and SDG 11
Mehryar and Surminski (2022)	Lowestoft, England	Investigating how a combination of modelling and measurement methods can help decision-makers with their flood resilience strategies	Environmental and Natural Hazard: Co-benefits of resilience planning for flooding	Provided a Flood Resilience Measurement for Communities (FRMC) founded on a holistic and integrated conceptualization of community resilience capacity as comprising of human, social, natural, physical, and financial capitals, and 44 indicators of resilience used for measuring these five capitals' capacities.	Benefits of resilience planning for flooding, for example benefits associated with using flood protection measures	Co-benefits associated with resilience planning for flooding (co-benefits are not specifically mentioned)

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TABLE 1 (Continued)

Reference	Region	Study's main objective	Category of co-benefits	Evaluation framework or assessment tool	Direct benefit	Co-benefits
Chabba et al. (2022)	Lima, Peru	Evaluating economic viability of Eco-DRR afforestation effort project through a BCA and include probabilistically estimated DRR benefits and place-based economic and non-market co-benefits representing stakeholder values.	Environmental and Natural Hazard: Co-benefits of Eco-DRR	A comprehensive assessment approach was designed using equity-weighted risk-based social BCA probabilistically assessed potential DRR benefits, integrated place-and context-based ecosystem co-benefits' values that influence social and ecological wellbeing, incorporated equity consequences for marginalized stakeholders by accounting for income differences, and addressed uncertainty in analysis through a stochastic BCA model using Monte Carlo simulations, and a sustainability analysis to monitor the Eco-DRR measure's contribution to broader urban resilience and sustainability goals that subjectively reviewed project performance, and benchmarked project impacts against IUCN's Global Standard and SDG 11 frameworks.	Benefits of afforestation conserve, restore, manage ecosystems which decreasing vulnerability against multiple risks by reducing exposure to hazards and increasing adaptive capacity	Avoided losses, property rights gains in the form of increased rent value
Yokomatsu et al. (2023)	Tanzania and Zambia	Introducing a dynamic macroeconomic model aimed at evaluating DRR policies under various hazards	Environmental and Natural Hazard: Co-benefits of DRR investment for natural hazard mitigation	Presented a model called DYNAMMICs to quantify the DRR benefits considering three resilience dividends, using RBC model as the basis for DYNAMMICs framework which simulates changes in investment, savings, consumption, and other variables due to external shocks, including disasters through a stochastic evaluation using Monte Carlo simulation.	Avoiding losses and damages from disasters (saving lives, reducing damages to infrastructure, reducing losses to economic flows)	Unlocking economic potential (household and agricultural productivity, land value from protective infrastructure), development co-benefits such as eco-system services, transportation uses, agricultural productivity gains
Rözer et al. (2023)	Vietnam, Nepal, Indonesia, Afghanistan, and the United Kingdom	Investigates knowledge gaps and challenges in integrating multiple resilience dividends into the planning, implementation, and evaluation of DRR interventions at the community level	Social, Economic, Environmental: Co-benefits of DRR investments	They suggested an analytical framework that incorporated the decision-making cycle by Brent (1998) and Mechler (2016) with the TDR concept to explore how various resilience dividends are integrated into different stages of a project and impact the outcomes of community-level DRR investment.	Reduced costal erosion, reduced flood damage, reduced damages to fishing boats and residential homes and businesses	Creation of new jobs through the restoration of hotels and other services, less out mitigation, increase agricultural yields, improved food and water security, more sustainable use of local resources

(Continued)

TABLE 1 (Continued)

Reference	Region	Study's main objective	Category of co-benefits	Evaluation framework or assessment tool	Direct benefit	Co-benefits
Sharifi et al. (2024)	Multiple locations worldwide	Providing a systematic review to addresses the scarcity of research exploring the connections between smart cities and SDGs	Social, Economic, Environmental: Co-benefits and trade-offs of SDGs	They performed a systematic literature review PRISMA method for literature search and selection using SCOPUS focusing on the connections between smart cities and SDGs. They used a deductive approach and emphasized different aspects like sectoral and geographic focus, methodological approaches, and linkages to SDGs. They further conducted co-occurrence analysis to accompany the review through mapping knowledge structures of the reviewed studies.	Major SDG benefits in categories including no poverty, good health, climate action, clean water and sanitation, affordable and clean energy	Accelerating economic growth, improving efficiency, strengthening innovation, and raising citizen awareness

gain support for mitigation actions, explore synergistic opportunities, and contribute to other objectives, such as increasing the efficiency and cost-effectiveness of climate actions (Cohen et al., 2021).

Green infrastructure has gained popularity for numerous purposes (e.g., stormwater management) since it provides multiple ecosystem services while improving urban sustainability and resilience. Therefore, various studies have developed frameworks to optimize the application of green infrastructure through the consideration of multiple objectives and accounting for their co-benefits (Alves et al., 2018, 2019; Meerow and Newell, 2017).

4.2 Co-benefits of resilience planning and sustainability

The co-benefits related to climate change (i.e., mitigation) and adaptation actions for the studies reviewed here are mainly categorized into two groups: health-related co-benefits and other co-benefits that cover a variety of environmental benefits such as air quality, soil and water quality, biodiversity, and economic and social co-benefits.

4.2.1 Health co-benefits of climate change mitigation and adaptation actions

Studies regarding health co-benefits of climate change mitigation actions have predominantly focused on quantifying such co-benefits through monetizing the reduction in mortality and morbidity due to improved air quality. The studies included have been primarily performed in East Asia and targeted emissions from sectors including transportation, industry, residential, and power (Li et al., 2019; Peng et al., 2017). There is consensus among the studies that the health and air quality co-benefits counterbalance the mitigation cost (Li et al., 2018; Markandya et al., 2018; Xie et al., 2018). Similarly, on a global scale and in the context of the Paris Climate Agreement, studies have shown that the health co-benefits would compensate for the mitigation cost of achieving the targets of the Paris Climate Agreement considering different scenarios where multiple countries contribute to emissions abatement based on equity criteria (Markandya et al., 2018). They found that while the value of co-benefits varies regionally, it exceeds the greenhouse gas (GHG) mitigation costs for most of the scenarios globally (Vandyck et al., 2018).

In addition to the studies that focus on monetizing health co-benefits, others have been selected for review in this section, including review studies and methodologies regarding incorporating health co-benefits into projects. Some studies provide systematic reviews of existing literature on the quantification of health co-benefits of mitigation actions. Quantitative estimates of health co-benefits of mitigation policies in the areas of air quality, transportation, and diet showed that health co-benefits of mitigation policies are a considerable part of their costs, and they often occur earlier compared to the direct benefits of reducing GHG emissions (Chang et al., 2017). Furthermore, the importance of quantifying the health co-benefits due to GHG mitigation is emphasized, as this information can assist policymakers in decision-making with regard to mitigation policies that affect the population on international, national, or regional levels (Gao et al., 2018). Review studies with regards to health and climate justice co-benefits have emphasized the importance of equitable data approaches to integrate community knowledge and qualitative data into climate planning, to enable collaboration across sectors. The complex interconnectedness of climate change and community health necessitates such cooperation (Kennedy et al., 2024).

4.2.2 Environmental and social co-benefits of climate change mitigation and adaptation actions

Most papers selected for this section are comprised of studies that have provided systematic reviews. The focus of these reviews covers a variety of topics, including reviews of available co-benefit assessment tools, reviews of the literature on NBS, reviews of documents with regards to co-benefits of climate policy and SDGs, and reviews of the literature on co-benefits of green infrastructure.

The systematic reviews about the co-benefits of climate mitigation actions in urban planning have been performed on a global scale, considering multiple cities as case studies. Measures such as green building programs, as well as distributed and decentralized energy systems that have a greater potential for providing co-benefits are discussed (Sharifi, 2021). Furthermore, these studies have shown that different cities worldwide differ in their capability to identify co-benefits or tradeoffs with mitigation in their adaptation plans. However, cities

TABLE 2 Summaries of studies selected for detailed content analysis with regards to co-benefits associated with climate change actions.

Reference	Region	Study's main objective	Category of co-benefits	Tool or assessment method for co-benefits	Direct benefit	Co-benefits
Chang et al. (2017)	Multiple locations worldwide	Reviewing studies quantifying the health co-benefits of climate change mitigation related to air quality, transportation, and diet	Environmental, social and economic: Health co-benefits of air quality improvements in both PM2.5 and ozone for achieving the 2°C climate mitigation	Reviewed the techniques used by other studies to quantify co-benefits. Multiple studies monetized the estimated health co-benefits to estimate the extent to which these benefits could offset the costs of implementing the policy.	Paris agreement: Reduce fossil fuel use to limit the temperature increase to 2°C and 1·5°C.	Health co-benefits achieved by mitigation policies and technologies that influence health by modifying health-related exposures such as non-GHG air pollutants, physical activity, and diet
Peng et al. (2017)	China	Examining near-term air quality and CO2 co-benefits of various current sector-based policies in China.	Environmental, social and economic: Climate and health co-benefits of air quality improvements	Calculated the mortality changes resulting from changes in air pollution levels for each scenario relative to their base mitigation scenario.	Reducing air pollutants: specifically reducing the $PM_{2.5}$	Health co-benefits based on mortality (due to ischemic heart disease, stroke, chronic obstructive pulmonary disease and lung cancer) changes resulting from changes in air pollution levels
Markandya et al. (2018)	USA, India, China, Europe, and the rest of the world	Analyzing how the health co-benefits would compensate the mitigation cost of achieving the targets of the Paris climate agreement.	Environmental, social and economic: Health co-benefits of air quality improvements in both PM2.5 and ozone for achieving the 2°C climate mitigation	Calculated the premature deaths and morbidity associated with concentrations of particulate matter and ozone in the atmosphere and monetized the health impacts using VSL.	Paris agreement: Reduce fossil fuel use to limit the temperature increase to 2°C and 1·5°C.	Health benefits of reducing air pollutants [fine particulate matter ($PM_{2.5}$); and ozone (O_3)].
Li et al. (2018)	China	Quantification of co-benefits using the example of energy-related co-benefits of CO2 mitigation	Environmental, social and economic: Improved health due to having improved air quality as a result of reducing GHG emissions	Calculated the co-benefits associated with avoided death based on the international value of statistical life (VSL).	GHG emission reduction	National health co-benefits (reduced mortality) from improved air quality due to reducing GHG emissions
Xie et al. (2018)	China, India, Japan, Rest of Asia	Quantifying the health and economic co-benefits of air quality improvements in both PM2.5 and ozone for achieving the 2°C climate mitigation goal in Asia.	Environmental, social and economic: Health (morbidity, mortality and expenditures and economic (Work time loss) co-benefits of air quality improvements in both PM2.5 and ozone for achieving the 2°C climate mitigation)	Combined the CMAQ model, a health assessment model, and the Asia-Pacific Integrated AIM/CGE model to evaluate the long-term health and economic impacts caused by ambient PM2.5 and ozone pollution under different climate mitigation and SSP2scenarios in Asian countries.	Reducing fossil fuel consumption and greenhouse gas emissions	Air quality improvement and decrease of premature deaths caused by exposure in PM2.5

(Continued)

TABLE 2 (Continued)

Reference	Region	Study's main objective	Category of co-benefits	Tool or assessment method for co-benefits	Direct benefit	Co-benefits
Vandyck et al. (2018)	Global	Assessing the global and regional mortality, morbidity, and agricultural air quality co-benefits in the context of the Paris Agreement while accounting for future uncertainty in air pollution control measures	Environmental, social and economic: Health co-benefits of air quality improvements in both PM2.5 and ozone for achieving the 2°C climate mitigation	Calculated the co-benefits of avoided premature mortality (monetized by using the VSLs), lost workdays, and crop yields. A hybrid approach that combines market and nonmarket benefits was used for the economic valuation of co-benefits. The market co-benefits for labor markets through a reduction of lost workdays due to illness (PM2.5) and for agriculture markets via improved crop yields (O3) were used as input in the global economy-wide CGE model JRC-GEM-E3 to assess the broader economic impacts.	Paris agreement: Reduce fossil fuel use to limit the temperature increase to 2°C and 1·5°C.	Health benefits of reducing air pollutants include reducing morbidity and mortality, and improvement in agriculture
Gao et al. (2018)	Global	Synthesizing the current evidence of public health co-benefits of GHG emissions reduction in different economic sectors to improve understanding of the mitigation measures involved, potential mechanisms, and relevant uncertainties	Social: Public health co-benefits of greenhouse gas emissions reduction	No Specific method is provided.	GHG emission reductions	Health co-benefits associated with GHG emissions reductions in different sectors including energy generation, transportation, agriculture and food, households, and industrial and economic processes.
Li et al. (2019)	China	Analyzing the air pollution co-benefits of low-carbon pathways toward the well below 2°C (WBD2) target in China.	Environmental, social, and economic: Improved air quality because of reducing GHG emissions and consequently decrease of premature deaths caused by exposure in PM2.5	No method explicitly mentioned for the calculation of co-benefits; however, multiple models are used to calculate energy consumption reduction, air pollution emission reduction, air quality improvement, and the number of premature deaths because of implementing constraints to reduce GHG emissions.	GHG emission reduction	Air quality improvement and decrease in premature deaths caused by exposure to PM2.5
Barron et al. (2019)	Australia	Proposing interventions that provide strategic green space enhancement at the neighborhood and block scale	Social and Environmental: Co-benefits associated with enhancing green spaces that improves both climate resilience and human health	Provided intervention typology and illustrative diagrams that presented various green space configurations and served as a guidance system for urban greening to optimize human health and climate resilience co-benefits. The interventions achieve spatially explicit functions while enhancing quality of life and experience. Each of the eight interventions reflect: a primary health benefit and/or a climate resilience response identified from the literature review, and a physical vegetation configuration in relation to other structural elements and spatial conditions.	Urban green spaces with primary objective of helping cities transition to more resilient, healthier, and sustainable futures	Positive effects of urban green space for human health

(Continued)

TABLE 2 (Continued)

Reference	Region	Study's main objective	Category of co-benefits	Tool or assessment method for co-benefits	Direct benefit	Co-benefits
Fernandez-Guzman et al. (2023)	South America	Evaluating the existing evidence on the health benefits of climate mitigation strategies in South American countries	Social and Environmental: health co-benefits of climate change mitigation strategies	They conducted a systematic review of studies related to climate mitigation and health for countries in South America, using PRISMA for extension for Scoping Reviews guidelines. The focus of studies were climate mitigation strategies, defined as interventions aimed at reducing GHG emissions or increasing GHG removal and sequestration, and health co-benefits, referring to improved public health indicators resulting from climate change mitigation actions. The authors considered studies, including trials, quasi-experimental, comparative, observational, and modeling studies, and case reports.	Benefits associated with climate change mitigation actions including GHG emission reduction	Reduce morbidity and improve quality of life, reduce mortality, increase life expectancy, and decrease disability-adjusted life years (DALYs), and improve well-being (physical, mental, and social)
Kennedy et al. (2024)	Cortes Island, British Columbia, Canada	Promoting community health and climate justice co-benefits using case study of a rural remote island	Social and Environmental: health and climate justice co-benefits	They conducted a five-phase project including (1) environmental scan, (2) community scoping interviews, (3) community engagement and planning forum, (4) scoping review on justice-informed community engagement, (5) survey development.	Climate change mitigation actions benefits	Health and climate justice co-benefits
Sethi (2018)	Multiple locations worldwide	Providing an understanding of theoretical literature on generating and estimating co-benefits in this inter-disciplinary area by reviewing available assessment tools, and in the process, identify the grey zones or research gaps.	Environmental and Natural Hazard: Co-benefits of climate, local environment and development are considered under different sectors such as Transport, local environment, GHG emissions, Energy, residential/commercial service sector, Waste, energy, urban planning, public health, air pollution, economy	An exhaustive review of 44 urban-co-benefit assessment tools 27 in mitigation and 17 in adaptation is performed. Gaps are mentioned.	Climate change mitigation actions (e.g., GHG emission reduction)	Climate co-benefits in urban areas
Deng et al. (2018)	Multiple locations worldwide	Providing a systematic review to assess the state of knowledge on the co-benefits of GHG mitigation by exploring typology of co-benefits, mitigation sectors, geographic scales, and the types of research methods used.	Environmental, social, and economic, natural, and resilience: co-benefits associated with GHG mitigation and including economic impacts, ecosystem impacts, health impacts, air pollutants, resource efficiency, conflict and disaster resilience, distribution impact, energy security, technological spillover/innovation, and food security	Performed a systematic review of papers which included bibliometric analysis, and network analysis. They further hand-code the papers resulting from the systematic review and develop and implement a typology of co-benefits research.	GHG emission reductions	co-benefits associated with economic impacts, ecosystem impacts, health impacts, air pollutants, resource efficiency, conflict and disaster resilience, distribution impact, energy security, technological spillover/innovation, and food security

(Continued)

TABLE 2 (Continued)

Reference	Region	Study's main objective	Category of co-benefits	Tool or assessment method for co-benefits	Direct benefit	Co-benefits
Ershad Sarabi et al. (2019)	Multiple locations worldwide	Performing a systematic review of the literature focusing on the NBS.	Environmental: Co-benefits associated with NBS	Performed a systematic review of publication focused on NBS as a theoretical concept, NBS adoption, management, planning and implementation using the Scopus search engine.	Societal challenges arising from climate change and urbanization	Social, environmental and economic
Dovie (2019)	No specific location was mentioned	Analyzing the state of the PaCA's Article 7 and links with co-benefits to enable adaptation to independently contribute to and match mitigation efforts, arguing that greater levels of mitigation alone could not reduce additional adaptation cost.	Environmental: Co-benefits of climate change mitigation and adaptation actions.	No Specific method is provided.	Climate mitigation and adaptation	Co-benefits related to objectives of development, sustainability, and equity
Karlsson et al. (2020)	Multiple locations worldwide	Presenting a review of articles focused 'co-benefits' of climate policy with the purpose of accommodating policymakers in identifying research gaps by structuring, describing, analyze and synthesizing the rapidly expanding knowledge on climate policy co-benefits.	Environmental, social, and economic: co-benefits associated with climate policies that include improving air quality, diet and physical activity, soil and water quality, economic and organizational performance, and energy security	Provided a systematic review using Scopus database. They narrowed down the resulted documents by exclusion of documents by a rating of each article independently by all authors and a full read-through, followed by some additional rejections. Information was gathered from the final list of papers that included parameters such as category of co-benefit, quantification and monetization of co-benefits, policy aspects, and research gaps.	Reducing climate change costs	Improved air quality, improved diet and physical activity, improved soil and water quality, improved biodiversity, improved economic and organizational performance, improved energy security
Sharifi (2021)	Multiple locations worldwide	Exploring two types of interactions between adaptation and mitigation measures, namely co-benefits and synergies through analyzing evidence reported in the literature	Environmental and Natural Hazard: Co-benefits with regards to adaptation/ mitigation plans in urban design and land use planning, transportation, building, waste, energy, green and blue infrastructure, water, urban governance, and behavioral issues	Database of studies including 56 papers that were relevant to urban climate change mitigation and adaptation interactions were collected and different information was extracted from these papers including primary objective (mitigation/adaptation/both), major contribution to mitigation, Major links to risks, or adaptive capacities improved (e.g., flooding, wildfire, extreme heat). Then co-benefits and synergies with regards to each category of sectors, e.g., transportation were discussed.	Climate change mitigation and adaptation actions	Co-benefits and synergies between urban climate change mitigation and adaptation measures
Choi et al. (2021)	Multiple locations worldwide	Providing a systematic review of papers, focusing on their climate benefits, relevant co-benefits and trade-offs, and the green infrastructure types that provide such climate benefits and co-benefits.	Environmental: Co-benefits associated with green infrastructure used for climate change adaptation such as	Presented a systematic review of 144 documents collected from Web of Science, Scopus, and Google Scholar. They focused on extracting information with regards to the climate change adaptation and mitigation benefits, the type of green infrastructure, and qualitative or quantitative information on co-benefits related to the climate benefits, trade-offs, or disservices.	Climate change adaptation	Water scarcity management, flood management, heat stress reduction, ecosystem resilience, renewable energy, energy use reduction, carbon storage, coastal flood protection.

(Continued)

TABLE 2 (Continued)

Reference	Region	Study's main objective	Category of co-benefits	Tool or assessment method for co-benefits	Direct benefit	Co-benefits
Boyd et al. (2022)	South Africa (Durban, Cape Town), UK (London, Manchester), India (Surat, Indore), Canada (Montreal, and Vancouver)	Taking adaptation programs and planning as a starting point and identifies whether potential co-benefits and trade-offs with mitigation are considered.	Environmental and Natural Hazard: Co-benefits of adaptation plans for climate impacts as identified in each city's adaptation plan. Following hazards are considered: flash floods, sea level rise, extreme heat, water scarcity, storm surge	Performed a detailed review of the adaptation plan for each city. Their view process included exploring city-level adaptation measures and their corresponding mitigation co-benefits or tradeoffs in four categories of policy strategies, hard infrastructure strategies, ecosystem-based strategies. Furthermore, they performed interviews to identify factors contributing to a city's approach to co-benefits and associated obstacles in implementing them.	Climate change adaptation actions	Mitigation co-benefits of climate change adaptation
Jones and Doberstein (2022)	Canada	Performing a scoping review of the hazards literature to clarify scholars' usage of the term 'co-benefits' in the field of hazard mitigation and adaptation.	Environmental and Natural Hazard: co-benefits in climate-affected hazard adaptation	Created a scorecard tool that considered six themes in papers for scoring co-benefits including: climate change mitigation, multi-hazard protection, human health, economy, society and culture and environmental health	Climate-affected hazard adaptation	Co-benefits associated with climate-affected hazard adaptation measures in categories of climate change mitigation, multi-hazard protection, human health, economy, society and culture and environmental health
Roggero et al. (2023)	Moscow, Paris, and Montreal	Addressing the disparity between the theoretical concept of co-benefits and their practical influence on local climate mitigation efforts in urban areas.	Environmental, social: air quality co-benefits from mitigation	They employed a case study approach to study climate action in three cities where there has been progress in climate mitigation and documented history of poor air quality. They included written sources, including official documents, policy assessments, journalistic sources, and research contributions, were used to reconstruct mitigation efforts from 1990 to the present. The analysis involved systematically reviewing documents.	GHG emission reduction	Improved air quality, energy savings, energy security
Lee and Liu (2023)	Guandu plain in Taipei city, Taiwan	Proposing alternative land use practices and evaluating their co-benefits in alleviating flood risks, using an energy synthesis approach	Environmental, Natural Hazard, and Economics: Co-benefits associated with NBS to alleviate flood risk	The methodology comprised three steps: identifying co-benefits through an expert workshop, proposing alternative land use practices, and evaluating co-benefits using energy synthesis.	Reducing flood risk	Education: environmental, food and farming, reducing habitat loss and fragmentation, tourism, and recreation groundwater recharge microclimate regulation, improving air quality improving public health

that aimed to account for co-benefits and tradeoffs in their adaptation plans were somewhat capable of planning for synergies. Additionally, co-benefits of adaptation measures were more readily identifiable compared to their tradeoffs, and cities more frequently employed specific types of co-benefits such as ecosystem-based strategies and building design measures. It is also discussed that the implementation of decision-making tools such as multi-criteria assessments can accommodate identifying co-benefits and trade-offs (Boyd et al., 2022).

In the area of green infrastructure, systematic reviews of studies have shown most of the literature focuses on environmental benefits such as water and air quality improvement and heat stress reduction. At the same time, about 30% of the papers investigated the trade-offs between the benefits and disservices of green infrastructure (Choi et al., 2021). A review of the literature focusing on NBS has illustrated their human and ecological co-benefits in addition to ecosystem conservation and restoration. For NBS, the most frequently observed enabler was reported to be developing partnerships between stakeholders followed by effective monitoring, knowledge sharing, financial instruments, plans and legislations, education, and training, combining with gray infrastructures, open innovation and experimentation, and appropriate planning and design (Ershad Sarabi et al., 2019).

The literature review focused on co-benefits of climate policy indicated that most papers are concentrated on co-benefits of improved air quality; however, when the study is performed on a larger geographic scale, the focus could also cover diet, physical activity, soil and water quality, biodiversity, economic performance, and energy security. The analysis results further suggested that the economic value of the air quality co-benefits can be equal to or exceed mitigation costs; however, only a small portion of the studies have monetized the co-benefits. Such knowledge can benefit decision-making for policymakers whose concern with mitigation costs can lead to suboptimal climate policies (Karlsson et al., 2020). The diversity of geographical areas can also affect the importance of co-benefits. Roggero et al. (2023) investigated the discrepancy between theoretical concept and practical influence of co-benefits on urban climate mitigation efforts considering three case studies of air quality co-benefits in Moscow, Paris, and Montreal. Their assessment showed the controversial role of air quality co-benefits across case studies from a key element of mitigation to a potential source of controversy. The authors highlighted the essential role of air quality co-benefits in decision-making regarding local climate policies despite this controversy.

The systematic review of literature related to co-benefits of GHG mitigation has identified the most frequently studied co-benefits to be the ecosystem impacts and economic activity co-benefits, while energy security co-benefits are the least studied. Furthermore, the most and least studied sectors were energy, industry, building, waste, agriculture, forestry, and other land use (AFOLU), and buildings, respectively. With respect to scale, most studies were conducted on a national level, followed by international and regional level analysis. Geographically, the concentration of most of the studies was in Europe, with Oceania, Africa, and South America having the lowest number of papers. Based on the methodology, most papers used social science analysis methods such as qualitative case studies, literature reviews, surveys, and interviews. Among the studies that used science and engineering methods, integrated assessment models, optimization models, simulation models, and life cycle assessments were most frequently used (Deng et al., 2018) (Table 2).

4.3 Analysis tools and methods

The proposed frameworks and tools of reviewed studies in the previous section are categorized into monetization methods, multi-criteria (i.e., multi-objective) analysis methods, scoring methods and matrices, and systematic reviews. Selection of methods and associated tools relates both to the co-benefit topic(s) under analysis and the interested party as well as the technical expertise of those conducting the analysis. Thus, understanding the breadth of these tools is important to user selection of which to engage with in valuation and evaluation of co-benefits. This is particularly important when non-market valuation is involved (Helgeson and Gore, 2024).

4.3.1 Monetization methods

The literature review reveals a wide range of monetization methods that vary in complexity and are typically case-study specific. Alves et al. (2018) presented an approach to incorporate monetized co-benefits of green-blue infrastructure into a cost–benefit analysis of flood risk mitigation measures. The multi-criteria method for measures selection proposed by Alves et al. (2018) was employed to identify locally relevant benefits and the applicable measures to achieve those benefits. The authors considered various interventions of green, blue, and grey measures and ranked them based on the decision makers' analysis. Using the ranking, various combinations of measures were further analyzed, and a final set of measures and their associated benefits was selected and economically evaluated. The economic valuation was based on the relationships among impacts on the environment and the consequent human welfare, usually estimated based on local data. For example, to monetize the value of green roofs, the annual benefits were calculated, including direct benefits, such as: improving air quality, carbon sequestration, increased roof longevity, and indirect benefits, such as: air quality due to energy savings (energy price) and carbon reduced due to energy savings (CO_2 value). Paunga and Lassa (2020) presented an assessment framework for DRR investment in 222 countries that included aggregation of investment across indicators: (1) financial investment (foreign investment, development assistance, gross domestic product (GDP), insurance penetration), (2) social investment (access to education, health and water, and sanitation), (3) early warning system investment (internet access, mobile phone access, public awareness, disaster monitoring, risk assessment), and (4) enabling environment (easiness of doing business, government effectiveness, the rule of law, corruption control, DRR budget allocation commitment).

Yokomatsu et al. (2023) presented a Dynamic Model of Multi-hazard Mitigation CoBenefits (DYNAMMICs) to quantify the DRR benefits considering three resilience dividends, including (1) avoiding direct impact (1st dividend); (2) enhancing economic potential (2nd dividend); and (3) generating sustainable development co-benefits (3rd dividend). The authors implemented a class of macroeconomic models called Real Business Cycle (RBC) models as the basis for the DYNAMMICs framework. This model simulates changes in investment, savings, consumption, and other variables due to external shocks, including disasters, through a stochastic evaluation using Monte Carlo simulation. The model compares the mean growth paths of an economy with and without DRR investment and computes the Total Growth Effect (TGE) of DRR investment. The TGE is comprised of three dividends of ex post damage mitigation effect, ex ante risk reduction effect, and co-benefit production expansion effect. Rözer

et al. (2023) suggested an analytical framework that incorporated the decision-making cycle by Brent (1998) and Mechler (2016) with the triple dividend of resilience (TDR) concept advocated by the World Bank to explore how various resilience dividends are integrated into different stages of a project and impact the outcomes of community-level DRR investment. The Triple Dividend of Resilience helps stakeholders in the decision-making process through assessment of an interventions' benefits using methods such as Benefit Cost Analysis (BCA). When the decision is made, TDR guides the monitoring and evaluation against the predefined targets. The evaluation process could involve empirical quantification of resilience dividends to provide crucial information for both monitoring the DRR success and informing future DRR efforts.

Helgeson and O'Rear (2018) developed an economic framework for evaluating investment in sustainability based on a case study of solar-plus-storage from an installed rooftop solar photovoltaic (PV) system. They employed life cycle costing (LCC) analysis that accounts for all costs related to the development, owning, operating, maintenance, repair, and end of life (including disposal) for a project. In their framework, they accounted for avoided damages and losses due to increased resilience by calculating the resilience-related values for cost per unserved electricity (CUE) in dollars per kilowatt hour ($/kWh) using the Interruption Cost Estimate (ICE) Calculator (Sullivan et al., 2015). The ICE Calculator is a "tool designed for electric reliability planners at utilities, government organizations or other entities that are interested in estimating interruption costs" (ibid.), which provides estimates of aggregated direct and indirect costs reported as the CUE. Additionally, the authors quantified the whole-building environmental impacts (e.g., land use, global climate change potential, human health) of alternative building designs using life cycle assessment (LCA) inventory data in conjunction with input–output (I-O) data in a hybrid life-cycle impact assessment (LCIA) framework. Fung et al. (2021) developed a computable general equilibrium (CGE) model to quantify economic co-benefits of investing in increased flood resilience at a high level, and to show how co-benefits are distributed throughout an economy, in the case of Cedar Rapids, Iowa. To calculate the co-benefits, the avoided losses (in terms of output, employment, and household income) are first quantified under a simulated flooding event for the 2007 time period (before resilience investments). Subsequently, the economic co-benefits are calculated based on positive exogenous shocks that occur in the absence of a natural disaster for both pre-and post-resilience time periods.

In the area of health co-benefits, Peng et al. (2017) calculated health co-benefits by evaluating mortality reductions due to changes in air pollution levels from different scenarios relative to the base case. Mortality is associated with four diseases (ischemic heart disease, stroke, chronic obstructive pulmonary disease, and lung cancer) as a result of long-term exposure to $PM_{2.5}$. Markandya et al. (2018) used the Global Change Assessment Model (GCAM) to explore emission pathways and abatement costs of scenarios across temperatures and climate change methods. The scenarios were used in an air quality model (TM5-FASST) and the concentrations of particulate matter and ozone in the atmosphere, and in turn the associated premature deaths, were calculated. Finally, value of statistical life (VSL) is employed to monetize the health impacts which are compared with the mitigation cost obtained from GCAM. Li et al. (2018) developed a method to evaluate co-benefits and cost. The approach included the regional emissions air quality climate and health (REACH) framework that combined an energy–economic model, the China Regional Energy Model (C-REM, "global general equilibrium model that resolves China's economy and energy system at the provincial level"), with an atmospheric Nature Climate Change Articles chemistry model, GEOS-Chem. They employed C-REM to simulate energy and CO2 emissions and air pollutants by 2030 considering three scenarios that aim to reduce CO2 intensity by 3, 4%, or 5% per year between 2015 and 2030. Then the health co-benefits are monetized (change in mortality due to change in $PM_{2.5}$) using three concentration–response functions and two health valuation methods.

Xie et al. (2018) integrated the Community Multiscale Air Quality (CMAQ) model, a health assessment model, and the Asia-Pacific Integrated Assessment/Computable General Equilibrium (AIM/CGE) model to assess the long-term health and economic effects due to ambient PM2.5 and ozone pollution considering multiple climate mitigation and SSP2scenarios. The health impacts were considered as mortality and morbidity and monetized as additional medical expenditures and VSL. Then they were converted into per capita work time loss (change in the labor participation rate) in the AIM/CGE model to determine macroeconomic impacts. Finally, the net benefit of climate mitigation was calculated using cost–benefit analyses. Vandyck et al. (2018) incorporated extensive datasets and models on emissions, climate, the energy system, the dispersion and impacts of ambient air pollutants, and the economy in order to quantify the impact of actual climate change mitigation policies suggested in the runup to the 21st Conference of the Parties in Paris. To quantify the co-benefits, a framework was used that accounts for market and nonmarket benefits. Labor market benefits were considered as the reduction of lost workdays due to illness, and agricultural market benefits were captured by improved crop yields. These are used as input in the global economy-wide computable general equilibrium (CGE) model JRC-GEM-E3 (Joint Research Centre general equilibrium model). This model "describes consumer and producer behavior; represents government policies such as taxes, subsidies, transfers, and emission caps; captures endogenously the international trade flows based on (changes in) relative prices; and includes macro feedback mechanisms via forward and backward supply chain linkages and via labor market, wages, and employment effects." The JRC-GEM-E3 model is also designed to evaluate the cost of climate change mitigation policies. The health co-benefits regarding avoided premature deaths are monetized using the VSLs (not entered in JRC-GEM-E3 model).

Li et al. (2019) presented a model that combined the China TIMES model developed by the. Energy Technology System Analysis Program (ETSAP) of the International Energy Agency (IEA) (typically used for estimating carbon mitigation strategies and future energy systems in China) and the Greenhouse Gas and Air Pollution Interactions and Synergies model (GAINS) models (developed by the Air Quality and Greenhouse Gases (AIR) program at the International Institute for Applied Systems Analysis, IIASA). The GAINS model is a comprehensive assessment model that considers the interplay of different policies addressing both air quality enhancement and greenhouse gas emission reduction to evaluate the co-benefits of air quality improvement. The health impacts were accounted for as premature deaths from $PM_{2.5}$ based on the number of people in different exposure classes and GBD-2013 integrated exposure-response functions. The GBD-2013 (Global Burden of Disease Study

2013), conducted by the Institute for Health Metrics and Evaluation (IHME) at the University of Washington, provides a comprehensive evaluation of mortality, morbidity, and disability linked to diverse diseases, injuries, and risk factors worldwide, at both regional and national levels. The GAINS model quantifies the air pollutant emissions and $PM_{2.5}$ concentrations as well as the health impacts to evaluate the potential co-benefits under situations with and without air pollutant control technologies. After the mitigation targets are applied to the China TIMES model, the model computes scenario-dependent and cost-optimal profiles.

4.3.2 Multicriteria analysis methods

Multi-criteria analysis methods represent a class of methods used to evaluate the performance of alternatives (typically through optimization) with respect to multiple, potentially criteria (the objectives in an optimization problem). Meerow and Newell (2017) developed a Green Infrastructure Spatial Planning (GISP) model using a GIS-based multi-criteria evaluation (MCE) of six benefit criteria including stormwater management, social vulnerability, access to green space, air quality, urban heat island effect, and landscape connectivity and expert stakeholder-driven weighting with the objective of strategic placing of green infrastructure to maximize the co-benefits of planned green infrastructure.

Alves et al. (2018) proposed a multi-criteria decision analysis (MCDA) method for selection of flood mitigation measures in urban areas based on a multi-criteria analysis that considers flood risk reduction, cost minimization and enhancement of co-benefits. The authors discussed the innovative aspects of their proposed method comparing to previously available approaches that included accounting for grey measures in addition to green measures, involving various flood types in the analysis, and involving a wider range of co-benefits, and building the capability in the model to define preferences among these benefits. The method comprises several steps including screening (i.e., elimination of unapplicable measures according to flood type and local physical constraints), scoring (i.e., measuring performance assessment to enhance co-benefits and reduce flooding risk, measuring cost assessment considering total cost reduction), weighting (i.e., local preferences regarding co-benefits: first selection of weights, local preferences regarding final goal: second selection of weights), and ranking (i.e., final scores calculation and ranking development). The methodology proposed by Mehryar and Surminski (2022) was a combination of mental modeling, using Fuzzy Cognitive Mapping (FCM) and a resilience measurement method, using Flood Resilience Measurement for Communities (FRMC) with the objective of supporting a decision-making process regarding resilience measures. The authors first explored stakeholders' biases on flood resilience interventions, and then led them through a systems thinking exercise using FCM and FRMC to elicit mental models representing important aspects of flood resilience and their interrelations. These were then aggregated, representing the collective perceptions and knowledge of stakeholders, and used to identify the most beneficial resilience actions in terms of direct and indirect impacts on flood resilience. The model was then used to identify the level of agreement among stakeholders about aspects of flood resilience that required enhancement.

4.3.3 Scoring methods and matrices

Scoring methods and matrices represent less quantitative, often heuristic-based, alternatives to the highly complex monetization and multicriteria analysis methods. Presented a methodology to analyze National Disaster Resilience Competition (NRDC) BCA to examine a community's understanding of economic and environmental co-benefits, as reported in their BCAs and assessment methodologies used to quantify these co-benefits. The author created a table referred to as "The BCA crosswalk" to summarize the results from the NDRC BCAs. They developed codes (consisting of short phrases) to consolidate and represent the various types of co-benefits reported by applicants. The codes were used in the BCA crosswalk to represent high-level categories of co-benefits used in practice. Forty co-benefits were reported across three categories of co-benefits of community development (e.g., Housing supply, Traffic & reduced vehicle use), economic revitalization (e.g., renewable energy, workforce benefits), and environment (e.g., climate regulation, water filtration) in the BCA competition applications. Furthermore, the BCA crosswalk assigned a score for quantitative calculations of co-benefits ("1" if a monetary value was assigned and "0" if only qualitative descriptions were provided). The results of the analysis were provided in a series of visuals capturing the frequency and quantification of resilience co-benefits, showcasing the number of NDRC BCAs reporting co-benefits within each category and the percentage with monetary valuation, and the frequency and quantification levels across three co-benefit categories.

Mirhosseini et al. (2019) developed a matrix that weights the resilience and sustainability of certification systems (e.g., ENERGY STAR, PHIUS, FORTIFIED) and rating systems (e.g., RELi, Envision, LEED, BREEAM). The matrix delineates the extent to which external impacts including natural (e.g., earthquakes, storms, and hurricanes), environmental (e.g., climate change, extreme weather), social (society, health), and economic (economic risks) impacts have been addressed in the certification and rating systems based on a four-level scale. Furthermore, the matrix employs Woods' (2015) four basic concepts of resilience: (1) resilience as rebound, (2) resilience as robustness, (3) resilience as graceful extensibility, and (4) resilience as sustained adaptability to determine whether such concepts are considered in the mentioned programs.

Kurth et al. (2020) developed a scoring system to evaluate resilience co-benefits. Eighty-nine Engineering with Nature (EWN) coastal projects were reviewed, and their engineering strategies were determined and summarized as a list of 27 feature types (e.g., seawall with habitat growth opportunities). The contribution of each engineering feature type was evaluated with respect to resilience and US Army Corps of Engineers (USACE) business lines (i.e., flood risk management, navigation, ecosystem restoration). In evaluation of contribution of each feature to resilience, a rubric was used which breaks down resilience into four stages of the disaster lifecycle as outlined by the National Academy of Sciences (NAS) (National Research Council, 2012), plan/prepare, absorb, recover, and adapt. Under these four categories, 12 indicators were identified: (1) prepare (e.g., shoreline and/or sediment stabilization), (2) absorb (e.g., wave attenuation and/or dissipation), (3) recover (e.g., promotes self-recovery after hazard event), and (4) adapt (e.g., adaptability to changing community needs). Furthermore, an additional set of indicators were developed to measure the impact of EWN projects on specific USACE civil works programs to represent various civil works objectives, aiming to understand which types of USACE projects contribute most significantly to resilience. Ten indicators were defined under four other categories: (1) navigation, (2) management, (3) flood management and coastal storm risk reduction, and (4) environmental

restoration. Feature types were evaluated using a binary scoring system (0–1) for each indicator. A score of 1 is assigned based on whether the EDF report attributes a specific benefit to a feature. Finally, the scores were aggregated for resilience and USACE business lines.

Jones and Doberstein (2022) developed a scorecard tool related to co-benefits of climate-affected hazard adaptation. They started by performing a scoping literature review to extract examples of co-benefits from collected papers to identify common themes of co-benefits and define criteria for the scorecard. The common themes included climate change mitigation, multi-hazard protection, human health, economy, society and culture and environmental health. The scorecard contained three tables, in which the first table enabled decision makers to evaluate individual projects based on 18 defined co-benefits, grouped into six themes. The impact scores in the first table were based on the following categories: sacrifices (−2), hinders (−1), maintains (0), improves (1), expands (2), not applicable (0), and, not considered (−1). The second table assigned theme weights of 1 to 3 based on their importance in a specific context. The impact scores from the first table are multiplied by the theme weight in the second table to yield a project score. The third table could be used to compare the final score of the projects.

4.3.4 Systematic reviews

Finally, a more qualitative approach in the literature is to systematically review and analyze categories of co-benefits in existing studies. The review by Chang et al. (2017) provided a framework within which to discuss (for every category considered, including air quality, transportation and diet), the study approaches, policy scenarios at local, national, or international level, policy baselines, temporal scales, sources of GHG emissions, modeling considerations, concentration-response function considerations, and relevance and inclusion of co-harms. They summarized different methods employed by studies for valuation of health co-benefits that included VSL, value of life years lost with mortality analysis by age segmentation, benefits transfer approach, cost of illness, and willingness to pay. Fernandez-Guzman et al. (2023) conducted a systematic review of studies related to climate mitigation and health for countries in South America, using the Preferred Reporting Items for Systematic and Meta-Analysis extension for Scoping Reviews (PRISMA-ScR) method. The reviewed studies focused on climate mitigation strategies, which are defined as efforts to decrease GHG emissions (e.g., biofuel production) or increasing GHG removal and sequestration (e.g., coastal blue carbon, forestation,) and health co-benefits (i.e., public health indicators resulting from climate change mitigation actions). The review included different studies of trials, quasi-experimental, comparative, observational, and modeling studies, and case-study reports.

To better inform climate mitigation and adaptation planning processes at the region of study, Kennedy et al. (2024) conducted a five-phase project. The five phases included: (1) environmental scan, collecting and analyzing available datasets related to the island's environmental conditions to identify gaps for further research; (2) community scoping interviews, to complement the data gathered in first phase; (3) community engagement and planning forum, through forming a focus group to investigate climate change mitigation and adaptation strategies; (4) scoping review on justice-informed community engagement, including a systematic review of peer-reviewed and gray literature to identify best practices and recommendations for promoting justice in community engagement efforts for climate planning; and (5) survey development, synthesizing the findings of previous steps to develop a survey to obtain further insights from community members about climate change planning efforts.

Sethi (2018) evaluated and classified 44 co-benefit assessment tools into three groups: (1) informative or database tools, which provide information on specific urban, environment or development indicators that is helpful for government and policy makers; (2) evaluation tools, which allow users to evaluate the current situation, identify problems, and assess the most appropriate policy from set of options; and, (3) simulation tools, which could be used to model real-life situations and provide alternatives and future scenarios, impact assessment, and forecasts that can accommodate decision making. Sharifi (2021) provided a bibliographic analysis that included bibliographic coupling, co-citation analysis, and co-occurrence analysis, to explore the interactions between the existing knowledge about adaptation and mitigation. The author collected a database of studies including 56 papers that were relevant to urban climate change mitigation and adaptation interactions and different information was extracted from these papers including primary objective (mitigation/adaptation/both), major contribution to mitigation, major links to risks, or adaptive capacities improved (e.g., flooding, wildfire, extreme heat). Co-benefits and synergies with regards to each category of sectors, e.g., transportation were then discussed.

Choi et al. (2021) presented a systematic review of 144 documents collected from Web of Science, Scopus, and Google Scholar. They focused on extracting information with regards to the climate change adaptation and mitigation benefits, the type of green infrastructure, and qualitative or quantitative information on co-benefits related to the climate benefits, trade-offs, or disservices. Ershad Sarabi et al. (2019) performed a systematic review of publications focused on NBS as a theoretical concept, NBS adoption, management, planning, and implementation using the Scopus search engine. The analysis of the final set of papers was aimed at identifying the conceptualized NBS, objectives of NBS, key stakeholders in developing NBS, and the barriers and enablers for implementation and uptake of NBS. Karlsson et al. (2020) conducted a systematic review using the Scopus database. They refined the search results by independently evaluating each document using a rating system, followed by a full read-through. Afterward, they further narrowed down the selection by rejecting some additional documents. Information was gathered from the final list of papers that included parameters such as category of co-benefit, quantification and monetization of co-benefits, policy aspects, and research gaps. Deng et al. (2018) conducted a systematic review that included a bibliometric analysis of the corpus of papers to provide information on main research subjects, lead authors and highly cited publications. They further used network analysis to visualize the results. Additionally, the authors performed a mapping analysis to group the papers based on co-benefits, sectors, areas of geographic focus, and methods.

An alternative to reviewing categories of co-benefits and method in the scientific literature is to review a community's policy documents. Boyd et al. (2022) performed a detailed review of the adaptation plan for each city considered in their study. Their review process included exploring city-level adaptation measures and their corresponding mitigation co-benefits or tradeoffs in four categories of policy strategies, hard infrastructure strategies, and ecosystem-based

strategies. Furthermore, they performed interviews to identify factors contributing to a city's approach to co-benefits and associated obstacles in implementing them. Roggero et al. (2023) employed a case study approach to study climate action in three cities where there has been progress in climate mitigation and documented history of poor air quality. They included written sources, including official documents, policy assessments, journalistic sources, and research contributions, to analyze mitigation efforts from 1990 to the present. The analysis of documents showed how local governments embodied the biophysical linkages between GHG emissions and air pollution reduction into their strategies and policies.

5 Discussion and limitations

While this review provides a taxonomy of co-benefits analysis tools—monetization methods, multi-criteria analysis, scoring methods and matrices, and systematic reviews—it is also important to support potential users in selecting the most appropriate approach for their specific problem or context. Different decision environments, resource constraints, stakeholder priorities, and data availability shape which tools are practical and defensible in use. One of the most critical factors in tool selection is decision context. For example, municipal planners evaluating infrastructure investments under grant or regulatory scrutiny may require monetized outputs to support benefit–cost analysis (BCA). In such cases, tools like life cycle costing (LCC), computable general equilibrium (CGE) models, or statistical valuation of health/environmental benefits may be appropriate—particularly when high-quality local data is available. Conversely, community-based organizations working on urban greening or disaster preparedness in low-capacity environments may prefer scoring frameworks or multi-criteria methods that are more participatory and transparent, allowing for integration of community values even with limited data. See Table 3 for a summary of co-benefit analyses indicating user type, decision context, recommended method type(s), potential key advantages, and associated limitations.

Scoring methods and matrices also offer value in early-stage or comparative assessments, especially when a diversity of objectives or stakeholder values must be considered. These methods tend to require less technical input while enabling structured prioritization. For example, a regional agency conducting a resilience planning charrette could use a scoring matrix to align proposed interventions with resilience dividends and social equity metrics. These approaches are well-suited for screening-level analysis, public engagement, or grant application processes where full monetization is not required.

Multi-criteria analysis (MCA) methods serve as a bridge between qualitative and quantitative approaches. They are particularly useful in multi-sector planning environments where decisions must account for conflicting objectives—e.g., balancing flood risk reduction with green space equity or economic redevelopment. MCA can support structured decision-making across disciplines and help reveal trade-offs, even in the absence of monetized data. Finally, systematic reviews and tool inventories are most relevant to researchers, technical consultants, or regional planning bodies tasked with developing new policy frameworks or comparing alternative evaluation methods. These approaches are useful for meta-analysis, tool benchmarking, or integrating cross-sectoral co-benefit considerations into strategic planning documents.

While the preceding review of the current literature highlights a broad spectrum of analysis methods and tools available for measuring co-benefits, it also demonstrates some limitations to a cohesive framework across different topic areas. The specific strengths and weaknesses of the categories that were identified (i.e., environmental vs. economic, environmental vs. health, etc.) remain largely unclear and as such point towards the need for additional data collection and analysis.

TABLE 3 Summary of co-benefit analyses indicating user type, decision context, recommended method type(s), potential key advantages, and associated limitations.

User type	Decision context	Recommended method type(s)	Key advantages	Limitations
Municipal planner/public agency	Infrastructure planning, grant applications, cost–benefit compliance	Monetization Methods (e.g., LCC, CGE, BCA)	Generates defensible, dollar-based outputs for funding or policy decisions	Requires high-quality data, technical expertise, time-intensive
Community-based organization (CBO)	Prioritizing local projects, stakeholder engagement	Scoring Methods, Multi-Criteria Analysis (MCA)	Flexible, participatory, low technical barrier	Less precise, may lack perceived rigor for external funding
Regional planning authority	Cross-sectoral investment or land use strategy	MCA, Systematic Reviews	Supports multi-objective trade-off analysis, adaptable across sectors	May require expert facilitation and consensus-building process
NGO/advocacy group	Policy framing, community resilience campaigns	Scoring Matrices, Narrative-Based Tools	Captures social and equity co-benefits, supports storytelling	Limited comparability or generalizability
Technical consultant/ evaluator	Tool comparison, method design, model validation	Systematic Reviews, Hybrid Methods	Synthesizes methods across cases, builds institutional knowledge	Often retrospective, resource-heavy
Academic/researcher	Theory development, method refinement, longitudinal study	All (esp. MCA, Monetization, Systematic Reviews)	Deep analysis, model refinement, cross-case insights	May lack immediate applicability or stakeholder relevance

These studies all commonly point out the need for further research, particularly more cross-disciplinary collaboration and integration.

5.1 Co-benefits of resilience planning and sustainability

The literature demonstrates potential to align resilience and sustainability planning through co-benefits. Several studies emphasize the importance of quantifying co-benefits in supporting fiscally sound investment decisions (Alves et al., 2019; Fung et al., 2021; Helgeson and O'Rear, 2018; Keefe, 2018). Socio-economic valuation plays a crucial role in creating cost-effective and sustainable options, including resilience investments (Helgeson and O'Rear, 2018). Moreover, investing in increased resilience yields benefits even in the absence of disasters, contributing to economic co-benefits including increased household income and regional output (Fung et al., 2021). Considering co-benefits also helps to identify efficient adaptation strategies, such as the green-blue-grey strategy for hazard-resilient infrastructure (Alves et al., 2019). Finally, consensus building among technical experts and the public sector is essential for quantifying resilience co-benefits in a benefit–cost analysis (Keefe, 2018).

In terms of implementation, potential synergies between sustainability and resilience strategies across different scales emphasize the need for cross-disciplinary approaches (Mirhosseini et al., 2019). Frameworks incorporating sustainability, resilience, adaptation, and vulnerability metrics are necessary at various levels, from the single asset (e.g., building) scale to the broader community (Mirhosseini et al., 2019). Moreover, a systematic framework accounting for synergies and tradeoffs between sustainability and resilience is crucial for effective operationalization (Cohen et al., 2021).

Finally, the framework of Disaster Risk Reduction (DRR) has the potential to not only saves lives, but also to promote development potential, as well as socio-economic and environmental co-benefits (Paunga and Lassa, 2020). The quality of both institutions and governance influences the amount of investment in DRR (Paunga and Lassa, 2020). Disaster risk reduction solutions on a city scale are necessary to address increasing socio-natural risks (i.e., risks that stem both from natural and human-made causes), while supporting optimal environmental and equity outcomes (Chabba et al., 2022). However, DRR tends to be aimed at and structurally adopted across the Global South. There may be applicability to this construct in the Global North as a means to further tie together resilience and sustainability planning with relevant co-benefits.

Recent research by Yokomatsu et al. (2023) highlights critical policy insights for DRR-associated investments. They argue that DRR strategies must consider all potential hazards, as focusing on a single threat could inadvertently increase vulnerability to others. Although DRR investments entail short-term costs, evaluating their long-term benefits can facilitate more informed stakeholder discussions and decision-making. Yokomatsu et al. (2023) also emphasize that optimal DRR strategies should combine complementary options rather than rely on singular interventions. This approach ensures efficient resource use and effective risk reduction.

However, challenges remain in integrating multiple resilience dividends into DRR planning, particularly in developing countries where institutional silos often obstruct comprehensive policy alignment. While DRR efforts are increasingly aligned with Climate Change Adaptation (CCA) and development policies, the predominance of techno-scientific approaches tends to prioritize hard infrastructure solutions, often neglecting social and environmental resilience dimensions. Innovative interventions like Ecosystem-based Adaptation face hurdles due to their complexity and the uncertainty surrounding their acceptance and potential co-costs. Despite these concerns, the long-term benefits of interventions with multiple resilience dividends are well-recognized. To address skepticism and bridge knowledge gaps, pilot projects demonstrating successful outcomes are essential. Furthermore, integrated decision-making frameworks that span the entire project life cycle are crucial for aligning DRR interventions with high-level policy targets (Rözer et al., 2023).

In the context of sustainable development, smart city solutions are seen as instrumental in advancing the Sustainable Development Goals (SDGs), particularly those related to sustainable cities (SDG 11), responsible consumption and production (SDG 12), affordable and clean energy (SDG 7), clean water and sanitation (SDG 6), and quality education (SDG 4). However, Sharifi et al. (2024) call for further research to explore the broader implications of smart cities for achieving the SDGs. This includes examining potential synergies, conflicts, and trade-offs beyond cost and energy efficiency. Empirical studies are needed to complement existing conceptual and theoretical research, providing a more comprehensive understanding of how smart city solutions can contribute to sustainable development.

In conclusion, while significant progress has been made in DRR, CCA, and sustainable development, there are still notable gaps and challenges that need to be addressed. Future research should focus on developing integrated frameworks, conducting pilot projects, and exploring the multifaceted impacts of innovative solutions like smart cities. By doing so, policymakers and stakeholders can make more informed decisions that enhance resilience and sustainability across various domains.

5.2 Health co-benefits of climate change mitigation and adaptation actions

Most of the literature on health co-benefits emphasizes how co-benefits of climate mitigation and adaptation efforts can help offset policy costs (Chang et al., 2017; Markandya et al., 2018; Peng et al., 2017; Xie et al., 2018). Of particular interest to this review, various modeling limitations and areas needing further research are identified within these studies (Chang et al., 2017; Markandya et al., 2018; Peng et al., 2017; Xie et al., 2018).

The shape of relative risk functions is crucial in assessing health benefits of air pollution reduction (Peng et al., 2017). The GCAM model explores emission pathways and abatement costs but does not consider damages beyond health damage due to limitations (Markandya et al., 2018). Labor productivity and indoor air pollution are important factors in quantifying health and economic co-benefits of air quality improvement (Xie et al., 2018). Finally, achieving Nationally Determined Contributions

(NDCs) in the Paris Agreement requires systematic reviews of health co-benefits at larger scales and with greater consistency (Chang et al., 2017).

Moreover, various uncertainties exist in evaluating air quality improvement co-benefits, including low-carbon targets, application rates of control strategies, and differences in methodologies and risk functions (Li et al., 2019). Challenges and uncertainties in health co-benefits assessment of GHG emissions reduction include developing credible scenarios, heterogeneous health impacts among different population groups, and various economic valuations of health outcomes (Gao et al., 2018).

Multi-model assessments can help evaluate combined uncertainties in the modeling chain (Vandyck et al., 2018). Improved exposure measurement, additional health endpoints, and revised estimates of disease burden can enhance understanding of air pollution's health impacts (Vandyck et al., 2018). Future research should focus on developing a coherent approach to incorporating multiple sources of uncertainty, thereby providing a more comprehensive and reliable assessment of the health co-benefits of climate change mitigation and adaptation actions. This can enable policymakers to make more informed decisions that maximize health benefits while addressing climate change.

5.3 Environmental and social co-benefits of climate change mitigation and adaptation actions

Beyond health considerations, most studies on environmental and social co-benefits of climate mitigation and adaptation are synthesis and meta-analysis papers that identify shortcomings and research needs, especially related to quantifying such co-benefits.

Notably, the role of air quality co-benefits is one that is increasingly recognized, but not thoroughly encompassed within analysis, research, and policy at present. Despite the limited integration into policies, air quality co-benefits do influence climate mitigation efforts in various ways and are notably difficult to measure. Decision-makers need to prioritize flexibility in enabling conditions for climate action, allowing local governments to prioritize co-benefits based on their specific context and identified goals and values. Transnational municipal networks can facilitate knowledge sharing in this regard. Secondly, the Roggero et al. (2023) highlight the need for a nuanced understanding of co-benefits and their interactions with climate action, especially regarding air quality. While air quality co-benefits do influence local climate action, their role varies significantly across different contexts, highlighting the need for tailored approaches and further research to understand and leverage their potential effectively (Roggero et al., 2023).

A few studies focus on the specific set of mitigation and adaptation actions that communities can take. Sethi (2018) discusses conceptual, methodological, empirical, and policy-governance gaps in assessing urban co-benefits, including insufficient scientific understanding, data limitations, and limited understanding of cities' roles in climate action. Sharifi (2021) highlights considerable knowledge on the co-benefits of adaptation and mitigation in urban areas but emphasizes the need for more information on their synergies and the importance of sectoral collaborations and integrated urban management approaches.

Other studies explore challenges with incorporating co-benefits into planning and policy. Boyd et al. (2022) identify obstacles in considering co-benefits in urban climate adaptation plans, including limited technical capacity and siloed approaches to climate planning in cities. Karlsson et al. (2020) outline areas for further research on climate policy co-benefits, such as quantification based on empirical data, exploration of co-benefits in policy and decision-making, and assessment of integrated policies addressing multiple Sustainable Development Goals (SDGs).

Finally, Choi et al. (2021) and Ershad Sarabi et al. (2019) highlight gaps at the intersection of climate, sustainability, and the environmental co-benefits. Choi et al. (2021) indicate areas for further research on climate benefits and co-benefits of Green Infrastructure (GI), including investigating indirect contributions to climate mitigation and exploring socio-cultural values of GI features. Ershad Sarabi et al. (2019) argue for more research on barriers and enablers of Nature-Based Solutions (NBS), as well as interactions among specific barriers and enablers.

6 Conclusions and future work

This paper provides an overview of the current state of practice in evaluating and measuring co-benefits, with a particular focus on resilience co-benefits related to environmental sustainability and climate and extreme weather event resilience. There is the caveat that bibliometric analyses may reveal academic research interests, which may be differentiated from topics considered in decision-making for policy and management. The topic of co-benefits is, by definition, highly related to real-world project options, and the majority of papers reviewed leverage case studies.

The study builds on Fung and Helgeson (2017) in providing advances in quantification since 2017, as well as in cross-domain applications. The literature review reveals two primary focus areas: co-benefits of resilience and sustainability planning, and co-benefits of climate mitigation and adaptation actions. The latter are further categorized as falling as either health co-benefits or environmental and social co-benefits of climate actions. Within the two broad focus areas, our study reviews research objectives, analysis region, co-benefit categories, direct benefits, and evaluation methods and assessment frameworks. Moreover, we provide a synthesis of analysis tools and assessment methods including monetization methods, multi-criteria (i.e., multi-objective) analysis methods, scoring methods and matrices, and systematic reviews.

Co-benefits are generally articulated as such because they are part of policy or behavioral changes that address multiple objectives, this can make for optimistic business cases. Relatively few papers note co-costs or co-disbenefits. Fung and Helgeson (2017) discuss co-costs in their analysis. Wenger (2015) and Helgeson and O'Fallon (2021) note the importance of co-costs. A "negative co-benefit" refers to a situation where mitigating one negative environmental impact inadvertently creates another negative impact, while a "negative externality" simply means a cost imposed on a third party by an economic activity, without the involved parties having to pay for that cost; essentially, a negative co-benefit is a specific type of negative externality where the unintended negative consequence arises from trying to address another negative

issue. Our current analysis did not exclude co-costs specifically, but also did not focus on this category explicitly.

Future work could build on this foundation by offering a practical decision-support guide that maps real-world use cases to tool types based on criteria such as scale, sector, data availability, time constraints, and stakeholder involvement. Such a guide would greatly enhance the accessibility and uptake of co-benefits analysis frameworks in diverse planning and decision-making contexts.

Monitoring and evaluating the effectiveness of co-benefit measurement over time is essential to improving the accuracy, credibility, and utility of resilience planning. As interventions unfold and conditions evolve, assessing whether the chosen measurement tools and methods continue to capture meaningful and relevant co-benefits—such as health improvements, ecosystem gains, or economic outcomes—is critical. Over the mid-and long-term, this ongoing evaluation helps identify where methods may need refinement, ensures consistency in tracking progress, and supports more informed decision-making. In this way, effective measurement itself becomes a key component of adaptive management, enabling learning, accountability, and optimization of co-benefit outcomes across time.

The present review reveals several other gaps and opportunities for both future research and applications. Since the primary goal of this study was to identify and categorize analysis tools and methods, we identify two key opportunities for future research. One opportunity is to develop more generic evaluation methods for co-benefits. While analysis tools and assessment methods range in complexity and scope, a common theme is that such tools tend to take the approach of being case-study specific. This is likely in part due to the complexity and case-specific aspects of co-benefits. However, there is an opportunity to explore areas of overlap in these methods, so that application of these methods can be more consistent to both allow comparison across case studies and to enhance replicability. Considering this observation and the preceding review, one recommendation is to focus on scoring methods and matrices, which provide a good balance of quantitative and qualitative evaluation, in the development of more generic analysis and assessment methods and tools.

The second opportunity similarly arises from the observation that analysis tools and assessment methods vary in complexity and scope. We note that there is a lack, and therefore a need, for validation of assessment methods for co-benefits. While assessment methods for resilience, in general, exist, especially metrics (e.g., Gu et al., 2023), the studies we review rarely validate the analysis tools and assessment methods they use, aside from stakeholder engagement. There is an opportunity to systematically evaluate these methods through monitoring and evaluation; we recommend this for future research.

Author contributions

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Comprehensive risk assessment of urban floods based on flood simulation and socio-economic vulnerability

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Urban flooding has become a global problem, seriously threatening the healthy development of cities and the safety of people's lives and property. Urban flood risk assessment can effectively identify potential hazardous areas and provide a basis for the development of targeted disaster prevention and mitigation strategies. However, the current urban flood risk assessment research is mainly based on the flood inundation or indicator evaluation system, the lack of inundation characteristic and hazard-bearing body socio-economic attributes of the comprehensive consideration, resulting in the assessment results and the actual flood risk there is a certain deviation. Therefore, this study integrated urban hydrological and hydrodynamic simulation technology and Fuzzy Matter-Element (FME) theory, proposed a comprehensive flood risk assessment method that takes flood inundation and socio-economic vulnerability into account, and quantitatively evaluates the flooding risk of Zhengzhou City under different rainfall return periods. The results indicate that low-risk zones are primarily located in the peripheral and fringe regions of Zhengzhou, whereas high and very-high risk zones are predominantly situated in the central urban area, particularly in the western Jinshui District, northeastern Erqi District, and northern Guancheng District. These areas are the old urban areas of Zhengzhou City which were constructed earlier, and are characterized by low drainage system construction standards, aging pipe networks, dense population and road networks, and high economic value. The results contribute methodological guidance and decision-making reference for urban flood management and control.

KEYWORDS

urban flood, comprehensive risk, fuzzy matter-element, socio-economic vulnerability, entropy weight method

1 Introduction

Floods are among the most frequent natural hazards worldwide. They may lead to serious environmental damage, property losses, and casualties in a relatively short period (Chen et al., 2019; Jun et al., 2023), threatening human lives and causing significant economic losses (Chen et al., 2023; He et al., 2021). According to statistics, floods have led to the death of more than 500,000 people worldwide

in the past 30 years (Liu et al., 2022). As climate change exacerbates rainfall intensity and sea-level rise, flooding is expected to become far more frequent in the next decades (Guan et al., 2023; Magnus and Ola, 2020). In this context, it is crucial to accurately assess the flood risk. By accurately identifying and assessing the flood risk, it can help urban managers take targeted risk response measures to decrease the impacts and losses caused by flood disasters (Tallar and Geldoffer, 2022; Guan et al., 2023).

To effectively identify and evaluate urban flood risk characteristics, researchers have proposed various assessment approaches, such as analysis of historical data, indicator-based evaluations, remote sensing techniques, and numerical simulations (Chan et al., 2024; Wu et al., 2021; Wu et al., 2020). Among them, indicator-based evaluation and numerical simulation method have emerged as the primary tools in flood risk analysis. Most of the indicator-based evaluations methods construct an index system covering multiple dimensions such as hazard factors, disaster-inducing environments, disaster-affected bodies, and disaster prevention capabilities, and use weighted comprehensive evaluation for risk classification. This method is simple, relatively easy to obtain data, widely applicable, and can capture the subtle changes in risk within the spatial scope, and has been extensive application in urban flood risk studies. Xu et al. (2025) selected 16 indicators from environ-mental sensitivity and vulnerability of disaster-affected bodies, and disaster prevention capabilities to establish a four-dimensional evaluation index system for urban flood risk. They used the TOPSIS method to evaluate the flood risk of 21 prefecture-level cities in Guangdong Province. The results indicated a concentration of high-risk areas in the Pearl River Delta, as well as in the western and northern regions. Deo et al. (2025) established a flood risk evaluation index system containing 21 thematic layers using morphological, hydrological, land, and socio-economic criteria. The analytic hierarchy process was employed to weight the indices, and the resulting risk distribution in Jaipur was validated through field surveys. The results showed that about 33% of the areas in the Jaipur area had urban flood risks, and the urban flood risks in the central and southern regions were relatively high. Although the indicator-based evaluations method has a wide application basis in flood risk assessment, it still has certain limitations. Firstly, the selection of indicators and the assignment of weights often rely on expert experience or subjective judgment, which may introduce human biases and affect the objectivity and stability of the assessment results. Secondly, the indicator-based evaluations method mostly focuses on the characteristics of socio-economic attributes, often ignoring the inundation characteristics such as water depth, and it is hard to precisely capture the spatial distribution characteristics of disasters (Chen et al., 2021).

The numerical simulation method can accurately reflect the inundation characteristics of each subtle space by establishing a hydrological and hydrodynamic model using fine underlying surface data (Liang and Guan, 2024; Liu et al., 2020; Ma C. et al., 2022), and more intuitively reflect the inundation risks of various regions within the spatial scope, effectively making up for the limitation that the index system method cannot intuitively reflect the inundation characteristics. In recent years, it has been extensive application in urban flood risk assessment. Zhu et al. (2024) proposed a refined urban flood simulation-based approach for evaluating flood risk. This study took Omihachiman City in Japan as the study area, accurately simulated the entire flood process by developing a numerical analysis model, and simulated and evaluated the flood risks under 10-, 50-, and 100-year return periods in Omihachiman City, Japan. Zhang et al. (2024) used Infoworks ICM to construct a flood risk identification model for the Macau Peninsula and delineated the flood risk areas in the high-density urban area of Macau according to the flood inundation results. The above studies indicate that numerical simulation methods illustrate flood severity by modeling inundation features within the region, effectively revealing the spatial pattern of flood risks. However, most of these studies ignore the socio-economic attributes (such as population density, economic losses, vulnerability of infrastructure, etc.) of the disaster-affected bodies in the inundated areas, resulting in the assessment results being unable to comprehensively reflect the actual impacts of floods on the lives and property safety of local residents. Therefore, how to effectively consider flood inundation and socio-economic vulnerability to more accurately reflect the urban flood risk still requires in-depth research.

To this end, this study introduces the Fuzzy Matter-Element (FME) theory and proposes a risk assessment approach that combines flood simulation and socio-economic vulnerability. Firstly, a hydro-hydraulic model is constructed to accurately simulate the urban flood inundation process. On this basis, considering the socio-economic, road traffic, and resident population vulnerabilities, an assessment method for the socio-economic vulnerability of urban floods is proposed. Finally, by combining the entropy weight method and the FME method, a comprehensive risk assessment model that considers both flood inundation and socio-economic vulnerability is constructed to quantitatively evaluate the flood risks in Zhengzhou City under different recurrence periods. The innovation of this study is to propose a more reasonable urban flood risk assessment method by integrating flood inundation and socio-economic vulnerability. The research results can provide new ideas for urban flood risk assessment and scientific basis for urban flood disaster reduction.

2 Study area and data

2.1 Study area

Zhengzhou City is the capital of Henan Province, which located in the central region of China. Its geographical coordinates range from 112°42′ to 114°13′ east longitude and from 34°16′ to 34°58′ north latitude (Figure 1). The average yearly rainfall of Zhengzhou City is 625 mm, and more than 60% of the rainfall is concentrated during the flood season, resulting in frequent extreme rainfall events in Zhengzhou City during the flood season.

Zhengzhou City is an important transportation hub in China. Since 1978, its social economy has developed rapidly. As of 2024, the gross domestic product of Zhengzhou City has reached 1.4 trillion yuan, with a permanent population of approximately 13 million people, and the urbanization rate is close to 80%. Intensified extreme rainfall and accelerated urbanization have made flood disasters in Zhengzhou City particularly prominent in recent years. The average losses caused by waterlogging disasters triggered by rainstorms in Zhengzhou City exceed 200 million yuan each year (Wu et al., 2021). In particular, on 20 July 2021, Zhengzhou City

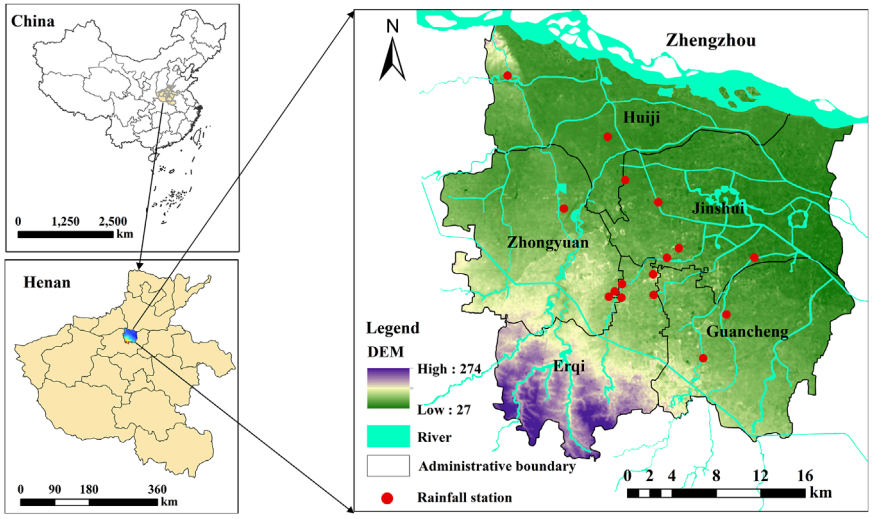


FIGURE 1
The location of study area.

experienced rare heavy rainfall. The hourly rainfall from 16:00 to 17:00 in the afternoon reached 201.9 mm, causing more than 2,000 residential communities in the urban area to be flooded, and water supply, power supply, and network services were cut off in many areas, having a profound impact on the economy, society, and ecological environment of Zhengzhou City (Dong et al., 2022). Therefore, a precise assessment of Zhengzhou's flood hazards holds significant value for strengthening local flood control and disaster reduction capabilities, optimizing emergency management strategies, and achieving sustainable urban development.

2.2 Data

In this study, the data sources mainly include the underlying surface data of Zhengzhou City (land use, drainage network, DEM, and building distribution), historical rainfall event data, population distribution, traffic road network, and urban functional zoning data. Among them, the underlying surface data of Zhengzhou City and historical rainfall event data are used for the construction and verification of the urban hydrological and hydrodynamic model; the population distribution, traffic road network, and urban functional zoning data are used for the urban socio-economic vulnerability risk analysis.

1. Underlying surface data: It includes land use, drainage network, DEM, and building distribution data. The land use information is obtained based on the processing of Pleiades satellite images, with 0.5 m spatial resolution. The drainage network data is provided by the Zhengzhou City Urban Management Bureau. The DEM is obtained from the Geospatial Data Cloud of Chinese Academy of Sciences, with a spatial resolution of 30 m. The building distribution is the vector data of building outlines in 2023, and the data set is provided by the Geographic Remote Sensing Ecological Network Platform (www.gisrs.cn).
2. Historical rainfall event data: The rainfall data is the three rainfall events on 26 July 2011, 1 August 2019, and from 19–21 July 2021, obtained from 16 automatic rain gauges in Zhengzhou City, with 10 min time resolution (update every 10 min). The data is provided by the Henan Provincial Hydrological Bureau. The ponding data under the three rainfall events is the ponding depth monitored by flood monitoring equipment, which is sourced from the Zhengzhou City Urban Management Bureau.
3. Population, road network, and urban functional zoning data: The population density data is sourced from the WorldPop project. The population raster data in 2020 with 100 m spatial resolution is selected. The traffic road network data is extracted from OpenStreetMap. The urban functional zoning data adopts the research results of Lv et al. (2023) on refined building data. The accuracy of the data of different functional areas identified by this result reaches 82.9%.

3 Methods

3.1 Urban flood model construction and inundation process simulation

3.1.1 Basic principles of PCSWMM

PCSWMM (Personal Computer Storm Water Management Model) is a comprehensive hydro-hydraulic modeling platform constructed by the Computational Hydraulics Institute of Canada based on the framework of SWMM (Storm Water Management Model) developed by the U.S. Environmental Protection Agency (EPA) (Ahiablame and Shakya, 2016). The core feature of PCSWMM lies in its integrated modeling capabilities, supporting fine-grained analysis of urban precipitation runoff, storage, and water balance under various rainstorm scenarios. In addition, by perfectly integrating GIS functions, this software enables users to build

models more intuitively using spatial data and visualize the results, thereby enhancing the scientificity and effectiveness of decision-making. In recent years, PCSWMM has been widely used in flood risk assessment, pollutant source tracing, and drainage system optimization (Bibi et al., 2023; Ma C. et al., 2022; Xu et al., 2023). In this study, PCSWMM was selected to construct an urban hydrological and hydrodynamic model to simulate the urban flood inundation process.

PCSWMM adopts a modular design, mainly including surface runoff generation and concentration calculation module, surface runoff concentration calculation module, pipe network runoff concentration calculation module, two-dimensional surface overland flow calculation module, and one-two-dimensional coupling calculation module. Among them, the two-dimensional surface overland flow and one-two-dimensional coupling calculation modules are the core of the PCSWMM model construction. In order to more accurately depict the surface inundation process, a building obstruction layer is set in the two-dimensional overland flow process model to simulate the obstruction of the flow path by buildings and the interference with runoff concentration. The one-two-dimensional coupling calculation module realizes the coupling of one-and two-dimensional models through two methods: "direct connection to a one-dimensional inspection well" and "connection using a bottom orifice." The detailed mathematical description and modeling process of PCSWMM have been introduced in previous studies (Ma C. et al., 2022; Xu et al., 2023). This study focuses on introducing how to comprehensively evaluate the urban flood disaster risk by integrating the results of flood simulation and socio-economic data.

3.1.2 Model validation

Model validation is the key to assessing whether a model can accurately simulate the flood inundation process. To fully verify the simulation effect of the constructed PCSWMM model on the flood inundation process, the measured water depth at waterlogging points were selected as the evaluation objects. The Nash-Sutcliffe efficiency coefficient (NSE) and the absolute value of the relative error (ARE) were used to evaluate the simulation effect of the constructed PCSWMM model on typical historical flood events, as shown in Equations 1, 2. According to the accuracy requirements for model calibration and validation (Ahiablame and Shakya, 2016; Ma B. et al., 2022), the NSE of the simulation results should not be less than 0.5, and the ARE should not be greater than 20%.

$$ARE = \frac{1}{n_s}\sum_{i=1}^{n_s}\frac{|x_i - y_i|}{y_i} \times 100\% \quad (1)$$

$$NSE = 1 - \frac{\sum_{i=1}^{n_s}(x_i - y_i)^2}{\sum_{i=1}^{n_s}(y_i - \bar{y})^2} \quad (2)$$

Where x_i is the predicted value, y_i is the measured value, n_s is the sample size, and $\bar{y}$ is the sample mean.

3.1.3 Urban flood simulation under different design rainstorm scenarios

In this study, the Chicago rainstorm method was adopted, and combined with the rainstorm intensity formula of Zhengzhou City, the rainfall process curves and rainfall amounts for the recurrence periods of 1, 5, 10, 20, 50, and 100 years were determined (Figure 2). The average rainfall peak coefficient was taken as 0.433, the rainfall duration was 180 min, and the rainfall intensity calculation formula was shown in Equation 3.

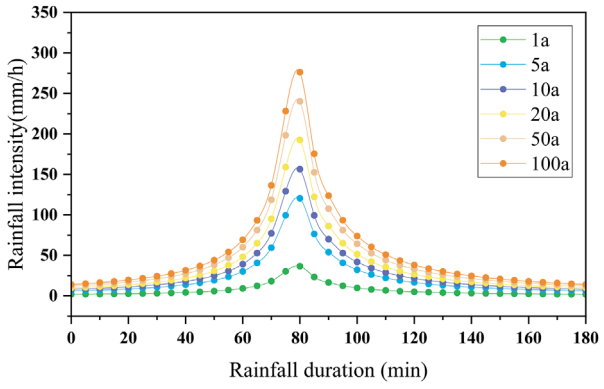


FIGURE 2
Design rainstorm hydrographs in Zhengzhou city (180 min).

$$i = \frac{q}{167} = \frac{2001.829(1 + 3.264 \lg P)}{167(t + 24.8)^{0.856}} \quad (3)$$

Where i represents the rainfall intensity (mm/min), q denotes the designed rainstorm intensity (L/hm3.s), P is the designed rainfall recurrence period, t signifies the continuous rainfall duration (min).

Use the validated urban hydro-hydrodynamic model to simulate the flood inundation processes with the recurrence periods of 1, 5, 10, 20, 50, and 100 years in the study area. Then, use the fishnet tool in ArcGIS to grid Zhengzhou City, set the grid scale to 200 m, and calculate the average value of the maximum water depth in each grid respectively, which is used to represent the ponding situation within the grid.

3.2 Socio-economic vulnerability analysis

3.2.1 Selection of socio-economic vulnerability indicators

The impacts of flood disasters on the urban socio-economic system are mainly reflected in aspects such as economic losses, traffic disruptions, and casualties. Therefore, starting from the actual impacts of urban floods on the economy, transportation, and population, this study selects a total of 8 indicators, including the number of submerged people, the submerged length of roads of different grades, and the economic losses in different functional areas, to construct an index system for urban socio-economic vulnerability analysis. The specific indicators are shown in Table 1.

3.2.1.1 Indicator of the number of submerged population

The indicator of the number of submerged population is one of the key factors in assessing socio-economic vulnerability. This indicator directly reflects the number of residents in the affected communities during flood disasters, thus revealing the degree of vulnerability of the population. The number of submerged people is closely related to the demand for rescue resources, social stability,

TABLE 1 Socio-economic vulnerability assessment index system for urban flooding.

First-level Index	Second-level Index	Third-level Index	Interpretation
Socio-economic Vulnerability	Society	Population	Number of submerged population
	Traffic	First grade Road	Length of submerged road (m)
		Second grade Road	Length of submerged road (m)
		Third grade Road	Length of submerged road (m)
	Economy	Industrial Area	Economic loss value of the industrial area (million yuan)
		Residential Area	Economic loss value of the residential area (million yuan)
		Public Service Area	Economic loss value of the public service area (million yuan)
		Commercial Area	Economic loss value of the commercial area (million yuan)

and post-disaster recovery capabilities. Understanding the number of submerged population is very important for formulating timely response measures and also provides necessary data support for subsequent post-disaster recovery and reconstruction.

3.2.1.2 Indicator of the submerged length of roads of different grades

The indicator of the submerged length of roads is an important basic variable for assessing the impact degree of flood disasters. From the perspective of transportation infrastructure, road inundation will directly affect the timeliness and coverage of emergency rescue operations. Once roads are inundated or damaged, the efficiency of dispatching rescue materials and personnel will decline significantly, making it difficult for the affected areas to receive timely support and thus exacerbating the vulnerability of the city. To more comprehensively reflect the influence of flood disasters on the urban transportation system, this study further refines the road grades and selects the submerged lengths of first-, second-, and third-class roads as refined indicators. Roads of different grades play different roles in the urban transportation system. First-class roads are usually urban main roads and are key channels for emergency rescue and material allocation; second-class roads are mostly sub-arterial roads, undertaking secondary traffic connection functions; third-class roads mainly serve the internal traffic of communities. Analyzing the inundation situation of roads of different grades helps to more accurately identify the influence of flood disasters on different levels of urban traffic networks, thus providing scientific support for formulating differentiated disaster-reduction strategies.

3.2.1.3 Indicator of economic loss

The indicator of economic loss is an key quantitative indicator for assessing the impact of flood disasters. This indicator not only covers direct property losses but also includes aspects such as industrial operation interruptions, business activity stagnation, and employment damage. Through a comprehensive assessment of economic losses, it can accurately capture the overall influence of flood disasters on the local economic operation. To more accurately reveal the economic impact of flood disasters on different functional areas of the city, this study refines economic losses into economic loss indicators for functional areas such as industrial areas, commercial areas, public service areas, etc. By analyzing the economic losses in different functional areas, it is not only possible to identify the key impact areas of flood disasters on the urban economic system, but also helpful to achieve scientific and precise allocation of post-disaster resources, and improve the city's response and recovery efficiency in the context of flood disasters.

3.2.2 Quantification of socio-economic vulnerability

3.2.2.1 Quantification of economic losses

In flood events, the economic losses sustained by hazard-bearing bodies are primarily determined by three factors: the inundation area, the unit economic value of the affected zones, and the damage rate associated with varying water depths. One of the widely accepted techniques for estimating such losses is the loss rate function method, which models how damage varies with water depth. Owing to structural and functional differences among various hazard-bearing bodies, their corresponding loss rate functions may differ considerably. To improve estimation accuracy, Lv et al. (2021) extracted flood impact data from 11 cities in China and established water-depth–based loss rate functions for different land-use types using the Beta distribution. This method effectively addressed the challenge of quantifying losses across diverse hazard-bearing categories. Based on their findings, this study applies the research results of Lv et al. (2021) to calculate the loss rates of four land-use types, namely residential, commercial, industrial, and public service, in flood disasters. On this basis, the losses of hazard-bearing bodies are calculated by combining the ponding characteristics of hazard-bearing bodies and the economic value of hazard-bearing bodies per unit area.

$$Loss = \sum_{m=1}^{M'} \sum_{j=1}^{J} Loss_m^j,\ j = 1, 2, ..., J; m = 1, 2, ..., M' \tag{4}$$

$$Loss_m^j = sp_m^j \times \sigma_m \times EV_m \tag{5}$$

Where $Loss$ represents the total loss. M' represents the number of types of hazard-bearing bodies used for loss calculation. In

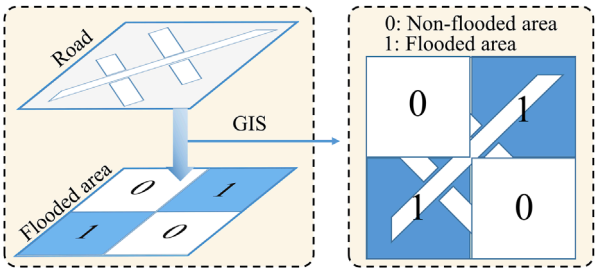


FIGURE 3
Evaluation framework diagram of affected roads based on GIS spatial overlay.

this study, the number of types of hazard-bearing bodies used for loss calculation is 4. J represents the number of hazard-bearing bodies under a certain type m of disaster-bearing bodies. $Loss_m^j$ represents the economic loss of the j-th hazard-bearing body within the m-th category of hazard-bearing bodies. σ_m represents the loss rate function for the m-th hazard-bearing type, which reflects the magnitude of the loss rate under a given water depth h. sp_m^j represents the inundated area of the j-th hazard-bearing body within the m-th category of hazard-bearing bodies. EV_m represents the value per unit area of the m-th type of hazard-bearing bodies. In this study, the economic value per unit area adopts the research results of Zhou et al. (2024).

3.2.2.2 Quantification of affected roads

In this study, the situation of roads affected by flood disasters is quantified by statistically analyzing the length of inundated roads under the influence of flood disasters. To accurately obtain the situation of roads affected within each inundated grid unit, ArcGIS spatial overlay analysis technology is adopted, and the spatial distribution data of roads is overlaid and analyzed with the flood inundation range. As shown in Figure 3, each grid unit is endowed with a dual attribute of "road length" and "whether it is inundated." For the grids identified as inundated, the total length of roads inside them is extracted and statistically analyzed, which serves as the quantification result of road damage within the unit. Furthermore, by summarizing the road lengths in all inundated grids, the spatial distribution characteristics of the degree of road damage at the regional scale are obtained.

3.2.2.3 Quantification of affected population

In order to achieve the spatial quantification of the affected population in different grids, the ArcGIS layer overlay analysis method is adopted to conduct spatial overlay analysis of the population and the distribution data of flood inundation. As shown in Figure 4, each grid unit is endowed with the attribute information of "population quantity" and "whether it is inundated." For the grids identified as inundated, the corresponding population quantity is extracted as the affected population data within the grid. Furthermore, by summarizing the population quantities in all inundated grids, the spatial distribution of the affected urban population at the planar scale is obtained, supporting the refined assessment of the affected population.

3.3 Comprehensive assessment of urban flood risk based on the FME method

3.3.1 Basic principles of the FME method

FME method is a coupled analysis method based on the theory of matter-element analysis and the theory of fuzzy mathematics, aiming at solving the problem of comprehensive evaluation of complex systems with multiple indicators, multi-dimensions and fuzzy boundaries (Chen et al., 2025; Lv et al., 2020). Its core idea is to describe the basic attributes of the research object through the matter-element triad, combined with the fuzzy affiliation function to quantify the uncertainty, so as to construct the dynamic correlation model, and realize the comprehensive analysis and classification of the complex system. Compared with the traditional risk assessment methods, the matter-element model allows the existence of a nonlinear coupling relationship among the feature indicators, and it supports the integrated analysis of natural-socio-economic composite systems (Lu et al., 2022). Therefore, the FME method was selected to assess the urban flood risk in this study. The construction of urban flood risk assessment model based on the FME method mainly contains the construction of indicator system, composite FME calculation, the assignment of indicator weights and the calculation of Euclidean discount schedule.

3.3.2 Construction of the indicator system

Choosing appropriate evaluation indicators is the key to assess urban flood risk. In the assessment of urban flood risk, rainfall, as a natural factor, directly affects the formation of floods. However, the single factor is not sufficient to comprehensively evaluate the urban flood risk, which is also influenced by socio-economic characteristics. For example, under the same submergence depth, the flood risk of high-value density residential areas is significantly higher than that of green spaces. Therefore, this study comprehensively considered flood inundation and socio-economic vulnerability in the flood risk assessment, selecting 9 indicators including Submerged depth (x1), number of submerged population (x2), submerged length of first-grade roads (x3), submerged length of second-grade roads (x4), submerged length of third-grade roads (x5), economic losses in industrial areas (x6), economic losses in residential areas (x7), economic losses in public service areas (x8), and economic losses in commercial areas (x9) (Figure 5). According to the characteristics of the selected indicators, the above 9 indicators are all of the larger the better type. Partial data on flood risk indicators can be found in Supplementary Table 1.

3.3.3 Complex FME calculation

Assume that there are m evaluation objects $(C_1, C_2, ..., C_m)$ for the feature indicators M in the flood risk assessment, and their corresponding fuzzy measure values are $u(x_1), u(x_2), ..., u(x_m)$, respectively. The m-dimensional composite FME R_{mn} of n feature indicators is constructed with m eigenquantity values of n feature indicators (Equation 6).

Among them, the fuzzy quantum value $u(x_{ij})$ in the FME model is usually the relative affiliation degree u(q) of each eigenquantum value, which is classified into the bigger and better type and the smaller and better type according to the indicator characteristics and roles, and the indicators of this study are all the bigger and better

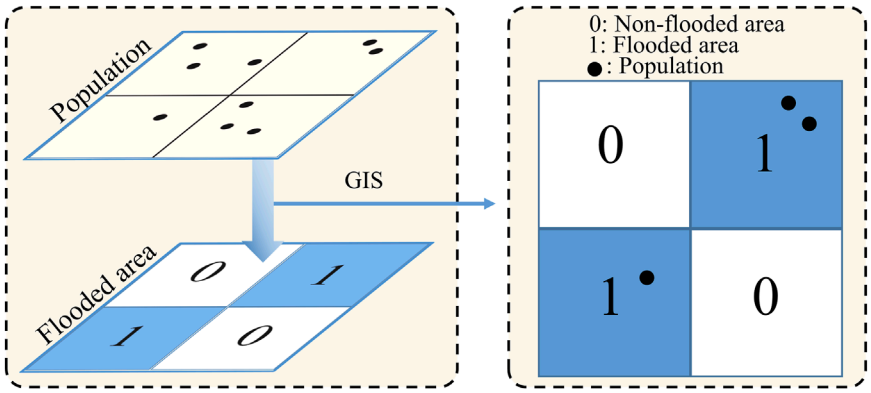


FIGURE 4
Evaluation framework diagram of affected population based on GIS spatial overlay.

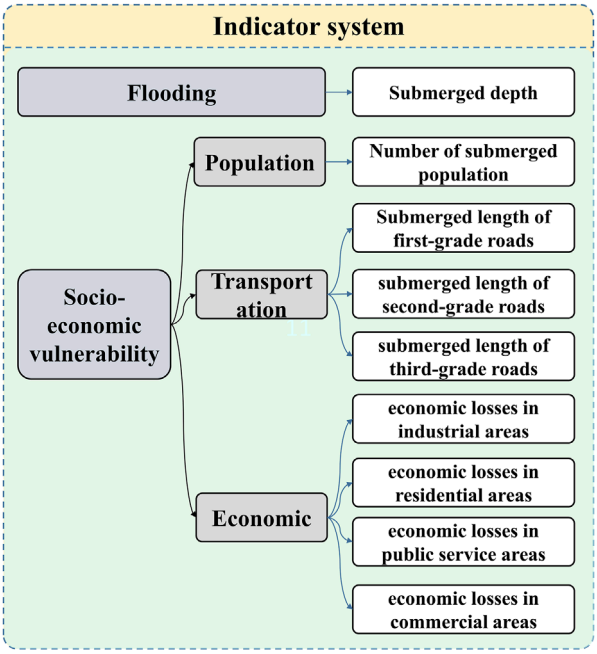


FIGURE 5
Comprehensive evaluation index system for urban flood risk.

type, and the computational formulas are shown in Equation 7.

$$R_{mn} = \begin{bmatrix} & M_1 & M_2 & \cdots & M_n \\ C_1 & u(x_{11}) & u(x_{12}) & \cdots & u(x_{1n}) \\ C_2 & u(x_{21}) & u(x_{22}) & \cdots & u(x_{2n}) \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ C_m & u(x_{m1}) & u(x_{m2}) & \cdots & u(x_{mn}) \end{bmatrix} \tag{6}$$

$$u(x_{ij}) = \frac{x_{ij}}{\max(x_{ij})} \tag{7}$$

Where M_j is the j-th feature indicator, C_j is the i-th evaluation object of the j-th feature indicator, and its corresponding fuzzy quantitative value is $u(x_{ij})$ $(i = 1,2,...,m;\ j = 1,2,...,n.)$. x_{ij} is the quantitative value corresponding to the i-th evaluation object of the j-th indicator; $\max(x_{ij})$ is the maximum value of all quantitative values x_{ij}.

Based on the composite FME and the principle of suboptimal subordination, the standard FME R_{on} is constructed (Equation 8). On this basis, the square of the difference of each term in the standard FME R_{on} and the composite FME R_{mn} is denoted by $(i = 1,2,...,m;\ j = 1,2,...,n)$. And the difference of the terms in the standard FME $R\triangle$ is obtained by using Equation 9.

$$R_{0n} = \begin{bmatrix} & M_1 & M_2 & \cdots & M_n \\ C_0 & u(x_{01}) & u(x_{02}) & \cdots & u(x_{0n}) \end{bmatrix} \tag{8}$$

$$R_{\Delta} = \begin{bmatrix} & M_1 & M_2 & \cdots & M_n \\ C_1 & \Delta_{11} & \Delta_{12} & \cdots & \Delta_{1n} \\ C_2 & \Delta_{21} & \Delta_{22} & \cdots & \Delta_{2n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ C_m & \Delta_{m1} & \Delta_{m2} & \cdots & \Delta_{mn} \end{bmatrix} \tag{9}$$

Where $\triangle_{ij} = \left[1 - u(x_{ij})\right]^2,\ i = 1,2,...,m,\ j = 1,2,...,n.$

3.3.4 Determination of weights based on entropy weight method

For the n characteristic indicators of the m evaluation objects, the m × n judgment matrix $X_{ij}(m \times n)$ is constructed, and the normalization matrix $P = p_{ij}(m \times n)$ is obtained by adopting extreme difference normalization for each indicator to eliminate the influence of the outline of each indicator on the flood risk assessment.

$$p_{ij} = \frac{X_{ij} - \min(X_{ij})}{\max(X_{ij}) - \min(X_{ij})} \tag{10}$$

Based on the results of indicator normalization, the weight d_{ij} of the indicator value of the i-th object to be evaluated in the j-th indicator is calculated. On this basis, the entropy value e_j of the j-th

indicator is calculated using Equation 12.

$$d_{ij} = \frac{X_{ij}}{\sum_{i=1}^{m} X_{ij}} \tag{11}$$

$$e_j = -\frac{1}{In(\mathrm{m})} \sum_{i=1}^{m} d_{ij} Ind_{ij} \tag{12}$$

Based on the entropy value for each indicator, Equation 13 is used to calculate the weights of each indicator w_j.

$$w_j = \frac{1 - e_j}{\sum_{i=1}^{n} (1 - e_j)} \tag{13}$$

3.3.5 Calculation of the progress of the european posting

By integrating the calculation results of the composite FME model and index weights derived from the entropy method, the Euclidean nearness degree was adopted to characterize the comprehensive index of urban flood risk in this study. As shown in Equation 14. Euclidean nearness degree is a quantitative method to measure the degree of proximity between the evaluation object and the ideal standard, which can comprehensively reflect the performance of each evaluation index on different risk units. Specifically, the nearness degree ρH_i indicates the distance between the i-th evaluation sample and the optimal standard sample, and the larger the value, the closer the sample is to the ideal state in each index, i.e., the lower the level of urban flood risk; on the contrary, it indicates that there is a higher flood risk in the region.

$$\rho H_i = 1 - \sqrt{\sum_{j=1}^{m} w_j \circ \Delta_{ij}} \tag{14}$$

4 Results

4.1 Urban flood model validation results

The 26 July 2011 rainstorm, the 1 August 2019 rainstorm, and the 20 July 2021 rainstorm events were selected to validate the model. As shown in Supplementary Figure 1 and Table 2, the ARE of the model's validation results under the three rainfall events did not exceed 20%, and the NSE was above 0.75 for all of them. From the accuracy under each validation event, the validation accuracy of the model for the 1 August 2019 rainstorm and the 20 July 2021 rainstorm event is significantly better than that for the 26 July 2011 rainstorm, which may be mainly due to the fact that the underlying surface data used in the model modeling are newer in recent years, and there are some differences in the characteristics of the underlying surface in Zhengzhou City during the 26 July 2011 rainstorm event, which led to the validation accuracy of the model for the 26 July 2011 rainstorm event is low. This also shows that the model accurately reflects the current underlying surface conditions in Zhengzhou and verifies the applicability of the model to simulate the current flooding in Zhengzhou.

TABLE 2 The ARE and NSE of the simulation results under 3 verification events.

Rainfall event	20 July 2021	1 August 2019	26 July 2011
ARE (%)	13.89	16.45	17.36
NSE	0.86	0.91	0.77

4.2 Flood inundation characteristics under different rainfall return periods

The flood inundation characteristics of Zhengzhou city for the rainfall return periods of 1, 5, 10, 20, 50, and 100 years were simulated using the validated PCSWMM model. As shown in Figure 6, with the increasing rainfall return period, the flooded area in Zhengzhou City continues to expand, especially from the once in 1-year to 5-year event, the largest increase in the flooded area. From once in 5-year to 10-year, the increase of flooded area has stabilized. For the once in 10-year rainfall event, the maximum depth of ponding in some areas of Jinshui and Erqi districts exceeds 0.6m, which affects the safety of vehicles and pedestrians (Guo et al., 2024). From once in 20-year to 50-year, the flooded area exceeding 0.6 m in-creases significantly. The flooded area where the depth of waterlogging exceeds 0.6 m further expands from the once in 50-year to the 100-year event. From the spatial distribution of the flooded areas, under the once in 100-year rainfall event, various regions of Zhengzhou City experienced different degrees of inundation, with more serious inundation in the northeastern part of Jinshui District, the northern and western parts of Guancheng District, and the northeastern part of Erqi District. Therefore, the management of Zhengzhou City should focus more on the potential flood risk of the bearers in these regions.

4.3 Results of socio-economic vulnerability assessments

4.3.1 Economic vulnerability

Based on the flood inundation results for different return periods, the economic losses within each affected grid for each of the four functional zones (residential, commercial, industrial, and public services) were calculated using the economic vulnerability quantification methodology of Section 3.2 and the spatial overlay tool of ARCGIS. On this basis, the economic loss results for the grids within each functional area were calculated using the zonal statistics tool of ARCGIS. As shown in Figure 7, with the increase of the rainfall return period, the economic losses in all four functional zones show a significant increasing trend, reflecting the significant impact effect of extreme rainfall events on the urban economic system. Among them, commercial and residential have the highest economic losses, mainly due to the higher asset density, complex building structure and high functional concentration within the commercial and residential unit area, where flood impacts will lead to higher direct property losses and potential disruption of

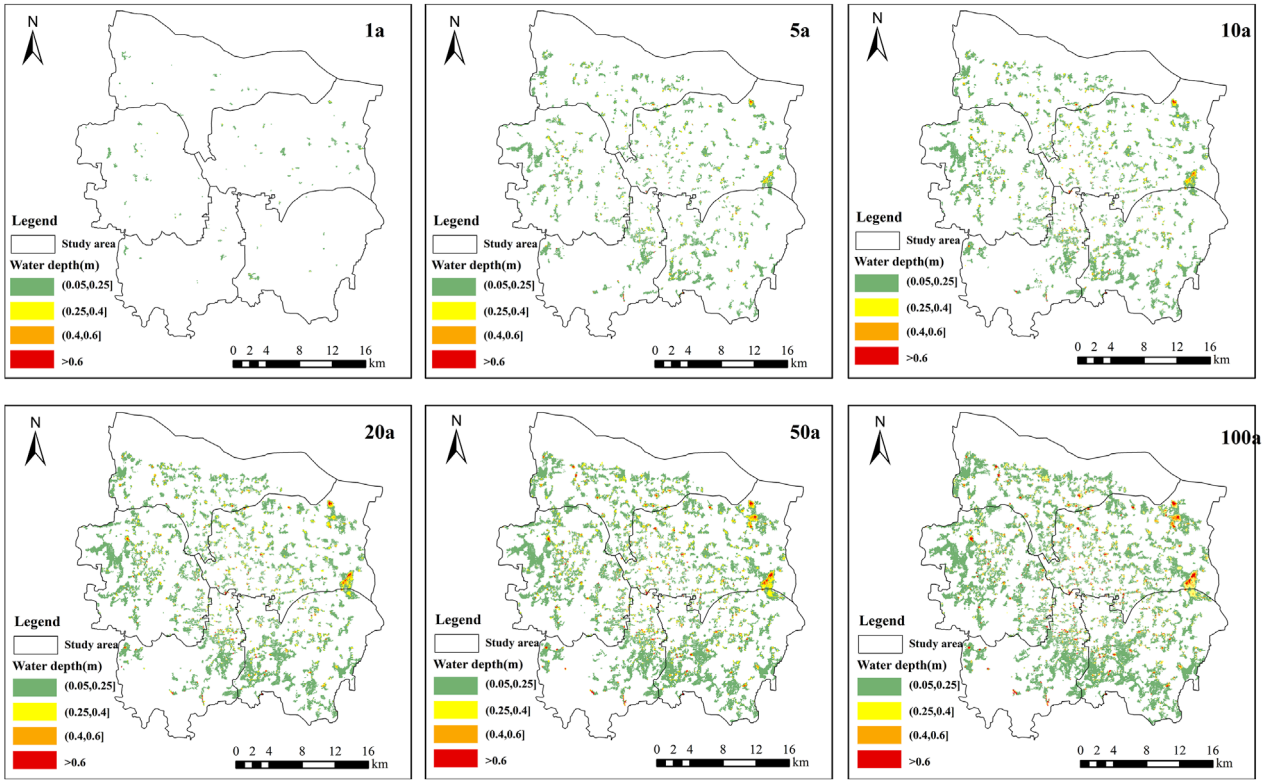


FIGURE 6
Flood inundation in Zhengzhou City under different rainfall return periods.

economic activities. In addition, commercial and residential areas tend to be located in central urban areas, where high levels of hardening and relatively limited drainage capacity exacerbate flood risk vulnerability.

In order to further reveal the spatial distribution characteristics of urban economic vulnerability, the spatial distribution characteristics of economic losses in Zhengzhou City under one-in-100-year rainfall event was analyzed. As shown in Figure 8, a large number of residential functional areas within Zhengzhou city suffered from different degrees of economic losses under the one-in-100-year rainfall event, which is the most prominent functional area of economic losses. The affected areas of commercial functional areas are mainly concentrated in the southern part of Huiji District, the northeastern part of Erqi District, the north of Guancheng District and the west of Jinshui District. These areas are characterized by intensive commercial activities and high building density, and the impact of flooding poses a significant threat to their economic operations and asset security. The affected areas in the Industrial Functional Area are sporadically distributed in the northern, western and southern parts of Zhengzhou City. The economic loss areas of the public service functional areas are mainly central Zhengzhou and the eastern part of Jinshui District, where public service facilities are more concentrated and bear a higher functional risk in flooding. Overall, under the scenario of one-in-100-year rainfall, different functional areas in Zhengzhou show significant spatial heterogeneity and risk distribution differences, indicating that flood prevention and control should be tailored to the characteristics of the functional areas to formulate targeted risk mitigation and resource scheduling strategies.

4.3.2 Transportation vulnerability

The road vulnerability quantification method in Section 3.2 was used to calculate the inundation of first, second and third grade roads under different return periods by combining the flood inundation results under different return periods. As shown in Figure 9, the total inundation length of roads at all levels showed a significant increase with the increase of rainfall return period. Among them, the most significant increase in the total inundated road length was observed from the once in 1-year to the 5-year rainfall event, especially for the second-grade roads, whose inundated length increased by nearly 10 times during this period, indicating that the vulnerability of the second-grade roads is more sensitive in moderate flooding events. The third-grade roads are the most severely affected road network level in flooding, because third-grade roads suffer greater inundation pressure in flooding due to not only their large number and wide distribution, but also due to the fact that drainage capacity of the third-grade roads is generally lower than that of second and first grade roads. It can be found that the road system in Zhengzhou City, in the face of different intensity of flooding events there are obvious differences in vulnerability, urban flood management needs to take into account the differences in road levels, optimize the drainage system and the layout of emergency access paths, focusing on strengthening

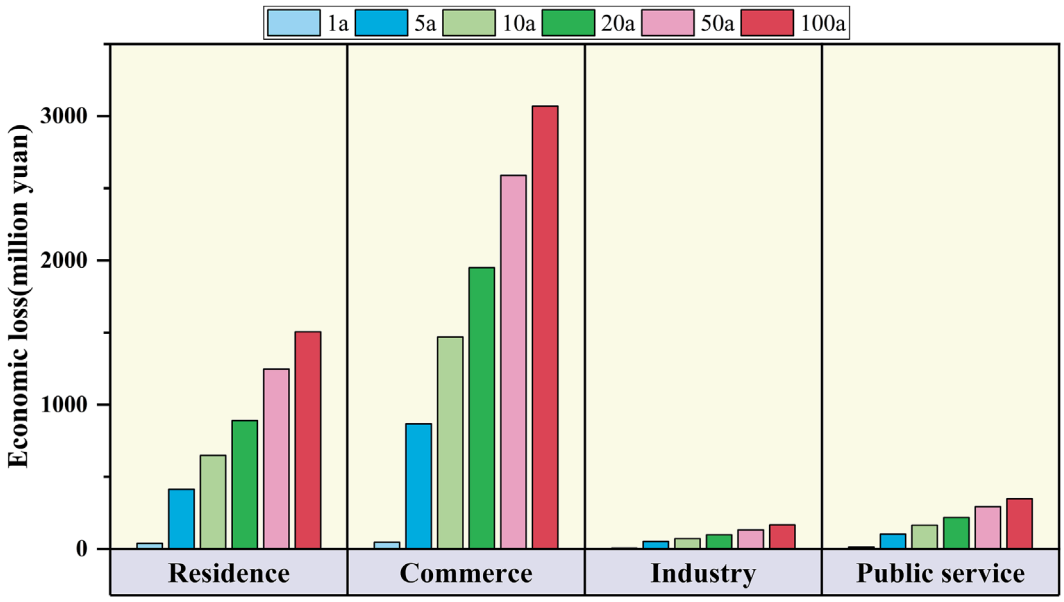


FIGURE 7
Economic losses in Zhengzhou City under different rainfall return periods.

the flood prevention capacity of the third-grade road area and emergency access security.

In order to further reveal the spatial distribution characteristics of transportation vulnerability, the road inundation characteristics in Zhengzhou City under the rainfall return period of once in 100-year was analyzed. As shown in Figure 10, the first-grade roads in central and southern Zhengzhou generally showed different degrees of waterlogging, with localized road inundation in the southern region being more serious. The inundation of second-grade roads is mainly concentrated in the central region of Zhengzhou. In contrast, the degree of inundation of the third-grade roads was significantly higher than that of first and second grade roads, reflecting its weaker resistance to flooding under extreme rainfall. The results are consistent with the analysis findings in Figure 9. Overall, the severely flooded roads are mainly distributed in the central and western regions of Zhengzhou City, exposing the obvious vulnerability of the region's transportation infrastructure under extreme weather conditions.

4.3.3 Population vulnerability

The GIS spatial overlay technique is used to overlay the spatial distribution of flood inundation with the spatial distribution of population, and the number of affected people in the statistical inundation grid characterizes population vulnerability. As shown in Figures 11, 12, the number of affected populations expands as the return period increases, and the distribution of affected populations shows a clear expansion trend. In particular, the increase in the affected population is most significant between the once in 1-year and 5-year rainfall return periods. In terms of the spatial distribution of the affected population, the affected population is mainly concentrated in the central and southwestern part of Jinshui District, the southeastern part of Zhongyuan District, and the southern part of Huiji District. These areas are the central urban areas of Zhengzhou, with frequent economic activities, high population density, and a high concentration of residential, commercial and public service facilities, leading to a higher risk of population vulnerability. Therefore, Zhengzhou city authorities should strengthen emergency protection measures for these areas during floods in order to minimize potential population casualties and secondary risks from flooding.

4.4 Comprehensive flood risk in Zhengzhou under different rainfall return periods

Figure 13 illustrates the results of the calculation of the weights of the assessment indicators under different rainfall return periods using the entropy weighting method. The results show that although there is a certain degree of fluctuation in the weights of the indicators under different reproduction periods, the overall situation presents a more stable and dominant characteristic. Among them, the submerged length of first-grade roads (x3), economic losses in industrial areas (x6), economic losses in public service areas (x8), and economic losses in commercial areas (x9) all show higher weights under each reproduction period, occupying a dominant position in the comprehensive risk assessment. Because the inundation of first-grade roads, as the main urban road network, in the event of flooding not only directly affects the evacuation of people and the deployment of emergency resources, but also causes extensive traffic disruptions and significantly reduces the operational efficiency of the city. Industrial, commercial and public service areas are the core of economic and social activities in cities, and severe inundation may lead to the disruption of industrial chains, the paralysis of basic services and the severe restriction of residents' lives. Therefore, city authorities should pay attention to

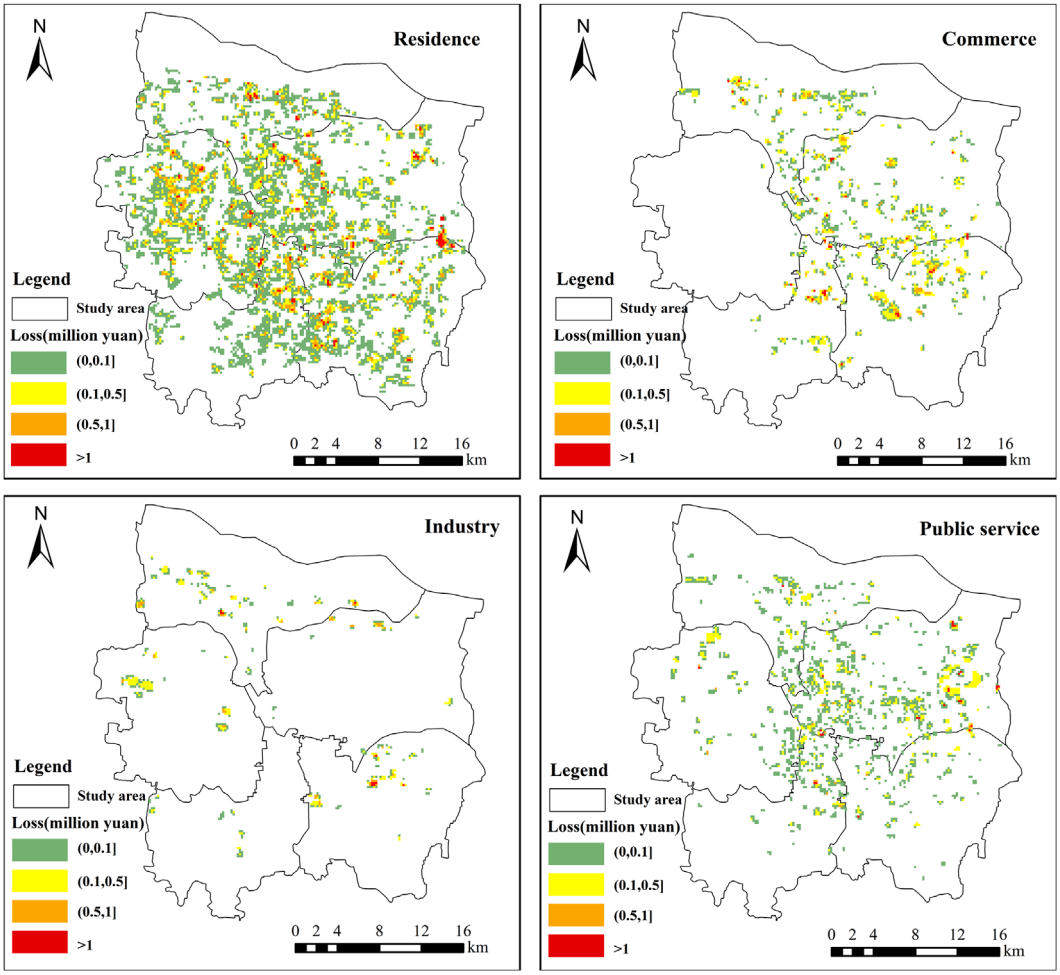


FIGURE 8
Spatial distribution of economic losses in Zhengzhou City under the rainfall return periods of 100a.

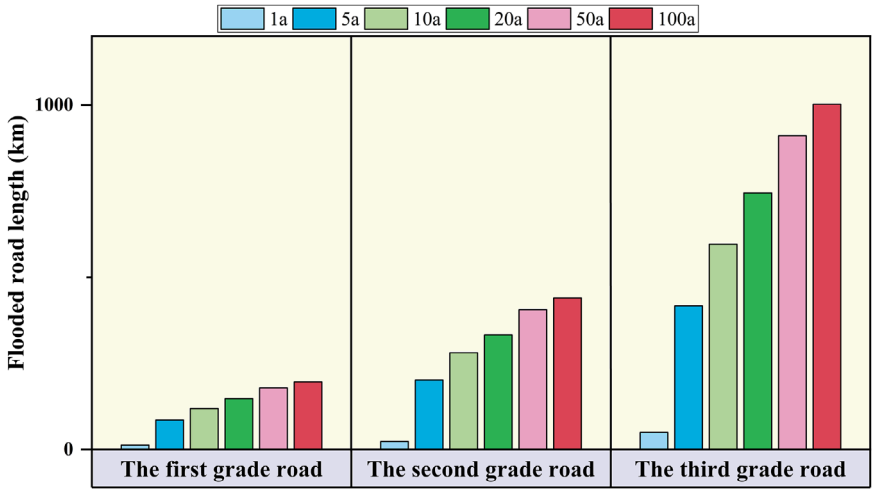


FIGURE 9
Flooded road in Zhengzhou City under different rainfall return periods.

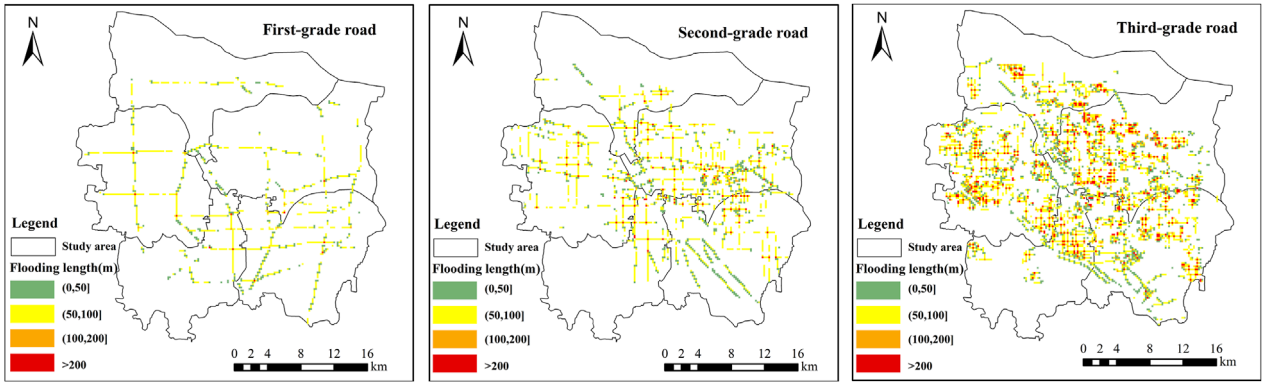


FIGURE 10
Spatial distribution of Flooded road in Zhengzhou City under the rainfall return periods.

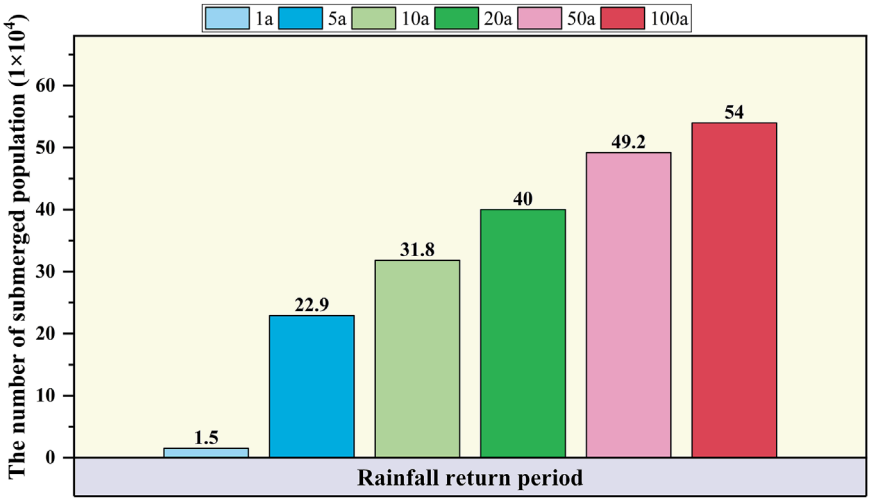


FIGURE 11
Submerged population in Zhengzhou City under different rainfall return periods.

the flood risk of roads and key economic and functional areas, and promptly activate drainage pump stations, allocate emergency resources such as drainage vehicles, water barriers, sandbags, so as to improve the resilience of the transportation and economic systems against flooding.

With the entropy method assigning weights to indicators, the FME method was applied to evaluate Zhengzhou City's flood risk under multiple rainfall return periods. As shown in Figure 14, as the return period lengthens, both the flood risk area and the risk intensity continuously expand and rise, especially between the increase of the rainfall return period from once in 1-year to 5-year, the risk changes are most significant. Comparison of the flood risk maps under the six different return periods reveals that the low-risk zones are primarily located in the periphery and fringe areas of the city, while the high-risk areas are concentrated in the central urban areas of the city, especially in the western part of Jinshui District, the northeastern part of Erqi District, and the northern part of Guancheng District. These areas are the older urban areas of Zhengzhou that were constructed earlier, and are generally characterized by low standards of drainage system construction, aging pipe networks, dense population and road networks, and high economic values, resulting in a significantly higher overall flood risk rating than other areas. Therefore, the authorities should focus more on the flood risk in these areas.

To further explore the spatial evolution characteristics of the comprehensive urban flood risk under the rainfall return periods of 1, 5, 10, 20, 50, and 100 years, the changes in the number of grids of different risk classes corresponding to each return period were statistically analyzed. As shown in Figure 15, as the return period lengthens, the number of grids of different risk classes shows an overall increasing trend, among which the change of the number of grids in low-risk and medium-risk areas is particularly significant. In contrast, the high-and very high-risk zones show a "rapid increase followed by stabilization", showing an obvious phased growth trend.

Specifically, from the stage of one in 1-year to 5-year, the scope of flooding impacts expanded rapidly, especially in the central Zhengzhou City where the capacity of the urban drainage system is weaker, resulting in the formation of large areas of waterlogging,

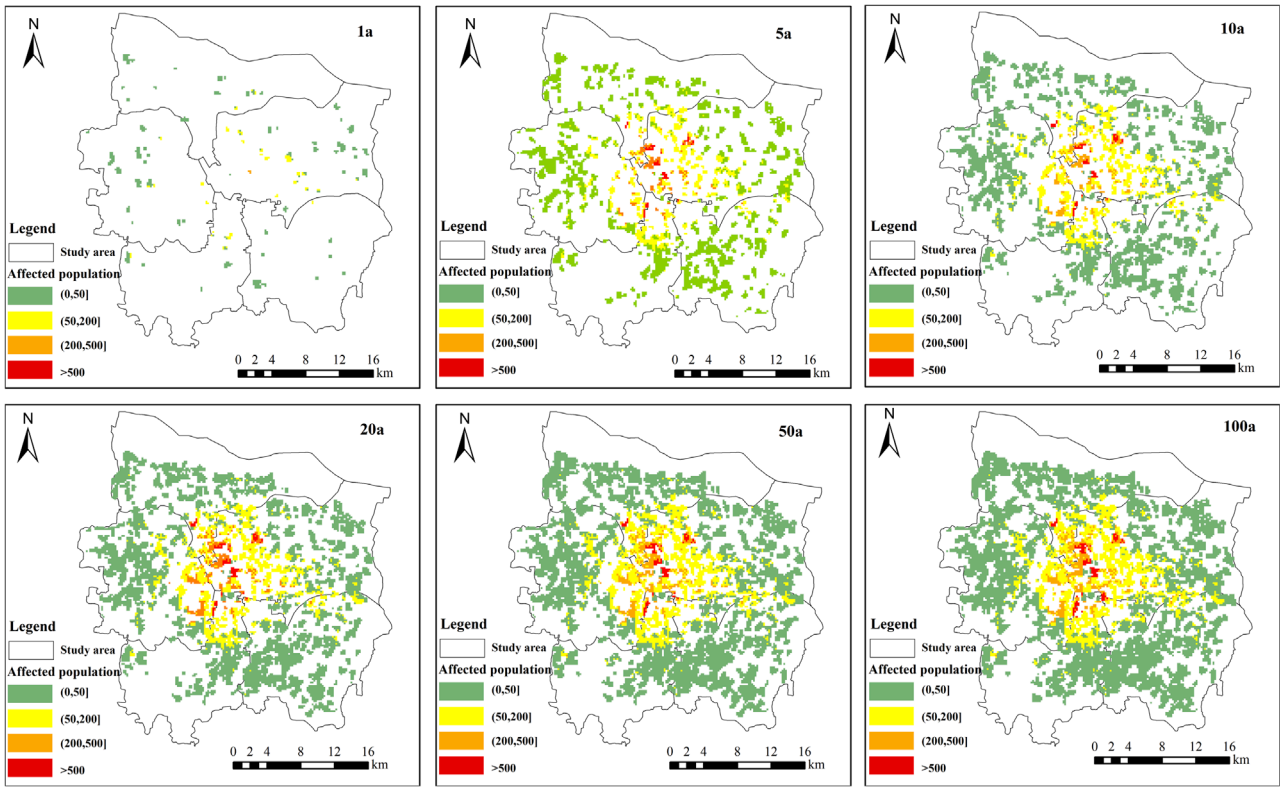


FIGURE 12
Spatial distribution of submerged population in Zhengzhou City under the rainfall return periods of 100a.

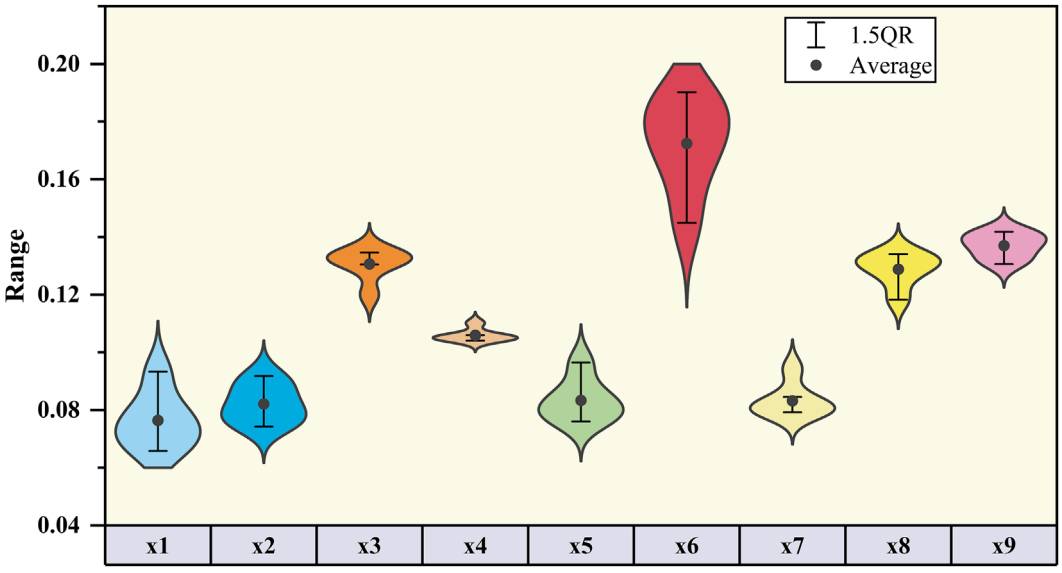


FIGURE 13
The indicator weights under different rainfall return periods.

which caused a substantial rise in the number of grids in low-risk and medium-risk areas. From the stage of one in 50-year to 100-year, the increase in the number of high-and very high-risk area grids tends to be slow, reflecting the limitations of the expansion of inundation space in the central city of Zhengzhou, although the overall risk level maintains an upward trend (Figure 6). This phenomenon is mainly due to the high rate of surface hardening, dense buildings, limited water retention capacity, and generally narrow river channels

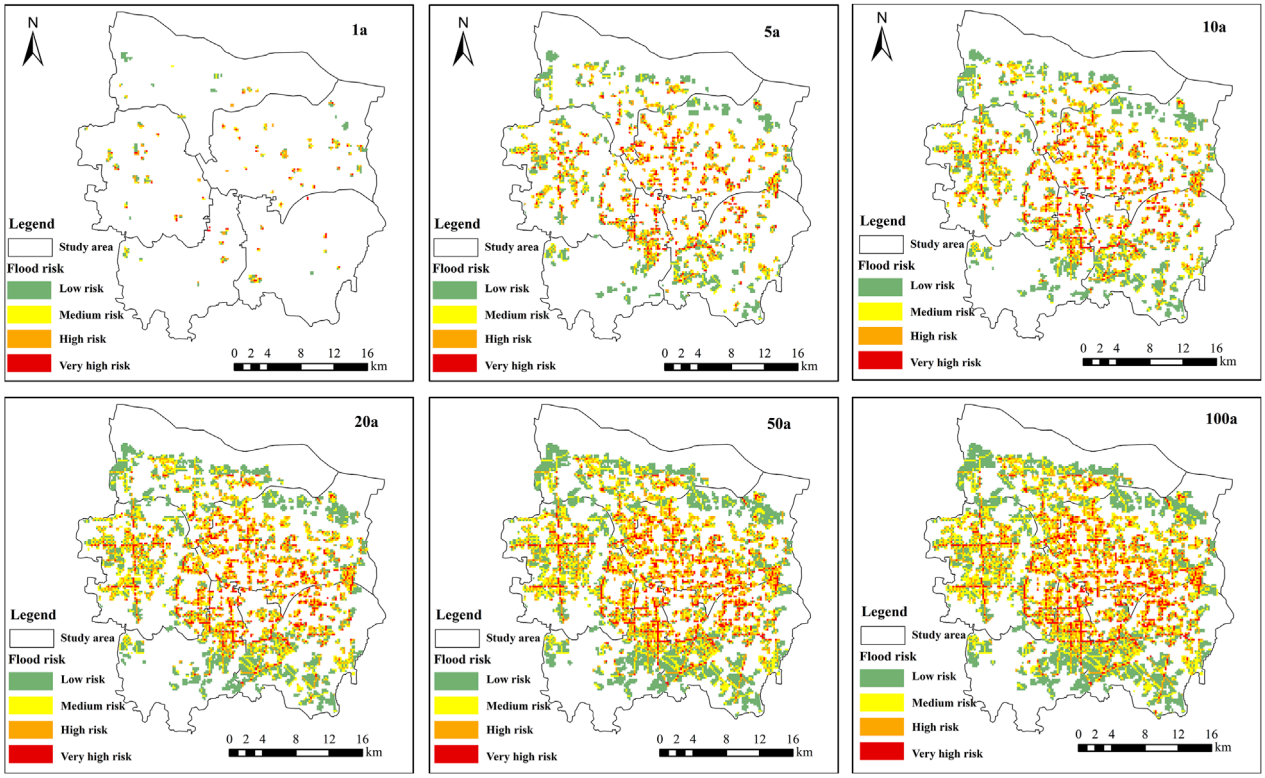


FIGURE 14
Comprehensive urban flood risk under six rainfall return periods.

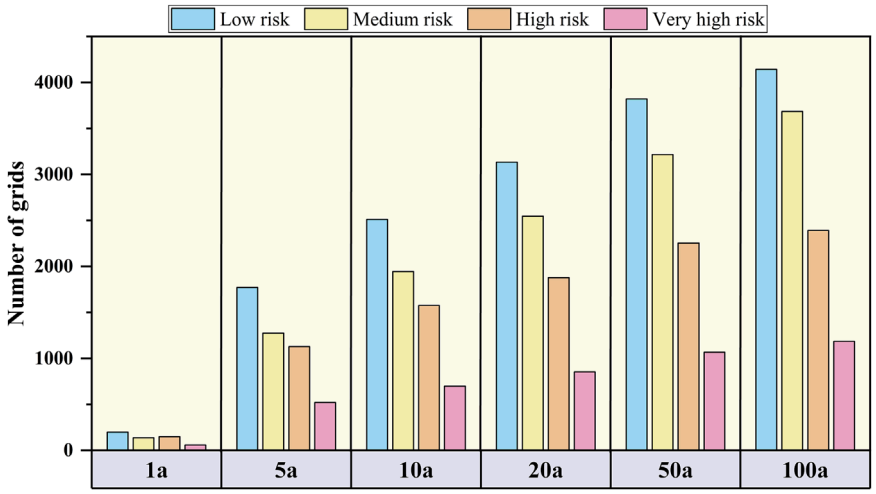


FIGURE 15
Number of grids for different recurrence periods and risk levels.

in central Zhengzhou, which makes it difficult for floodwaters to further break through the existing waterlogged boundaries under higher return period flooding scenarios, and makes the spatial extent of the high-and very high-risk zones tend to be stabilized.

However, this spatial "stabilization" does not mean that the level of risk is reduced. On the contrary, as the return period lengthens, the depth of waterlogging in the inundated area will increase significantly, which may induce secondary disasters and chain effects, such as waterlogging in underground spaces, interruption of power supply and paralysis of communications, and significantly exacerbate the disaster losses and social impacts in the severely waterlogged area. Therefore, the focus of risk control of more than once in 50-year rainfall event should be shifted

from spatial prevention and control of regional expansion to in-depth management of the core inundation area and resilience enhancement of key functional facilities. Urban management departments need to collect real-time water monitoring, flood simulation, and disaster reporting information during flood disasters to quickly identify key infrastructure risks in flooded areas. And by timely dispatching emergency resources such as sandbags, water blocking plates, and pumping pumps, ensure the safe operation of important areas, key projects, and critical regions.

5 Conclusion

The current urban flood risk assessment lacks comprehensive consideration of disaster hazard and socio-economic attributes of the hazard-bearing body, which leads to a certain deviation between the assessment results and the actual flood risk. Therefore, this study uses FME theory and PCSWMM hydrological and hydrodynamic simulation technology, constructed a comprehensive flood risk assessment model with comprehensive consideration of flood inundation and socio-economic vulnerability, and quantitatively evaluated the flood risk of Zhengzhou city under different rainfall return periods. The main research conclusions are as follows:

1. An urban one-and two-dimensional coupled flood simulation model based on PCSWMM was established to simulate the flood inundation characteristics of Zhengzhou City under different recurrence periods. The ARE of the model validation results under three rainfall events did not exceed 20%, and the NSE was above 0.75, which verified that the model can accurately simulate the flooding process in Zhengzhou City. The inundation simulation results of Zhengzhou city show that the serious areas of simulation are mainly concentrated in the northeastern part of Jinshui District, the northern and western part of Guancheng District, and the northeastern part of Erqi District.
2. Combining flood simulation results and socio-economic vulnerability quantification methods, the socio-economic vulnerability characteristics of Zhengzhou City under different recurrence periods are revealed. In terms of economic vulnerability, potential losses are mainly located in commercial and residential functional areas, and the central city with higher exposure and asset value is particularly affected. As for the road system, the third-grade roads show high functional vulnerability due to their weak drainage capacity and high coverage density, making them vulnerable weak links. Population high vulnerability areas are particularly prominent in the central city, where high population density and relatively weak infrastructure lead to greater risk in flooding.
3. Based on the entropy weight method and the FME method, a comprehensive flood risk evaluation model was constructed with comprehensive consideration of flood inundation and socio-economic vulnerability. The results of the comprehensive risk evaluation show that the low-risk zones are primarily located in the periphery and fringe areas of the city, while the high-and very-high risk areas are concentrated in the central urban areas, especially in the western part of Jinshui District, the northeastern part of Erqi District, and the northern part of Guancheng District. These areas are the older urban areas of Zhengzhou that were constructed earlier and are characterized by low drainage system construction standards, aging pipe networks, dense population and road networks, and high economic value. Therefore, Zhengzhou city authorities should focus more on the flood risk in these areas.

However, the limitation of the acquired data may lead to some uncertainty in the results of the comprehensive risk evaluation. In this study, static data on population density from the WorldPop project were used to assess urban flood risk, and although this method can reflect the basic population flood risk characteristics of different inundated areas, it fails to fully consider the spatial-temporal dynamic distribution characteristics of urban population. Future research can further combine multiple sources of dynamic data, such as cell phone signaling and population thermal, to explore the impact mechanism of urban population flow on flood risk at different times (e.g., morning and evening peaks) and in different cycles (e.g., weekdays and holidays), so as to better capture the spatial and temporal dynamics of urban flood risk, offering a stronger foundation for urban flood prevention and control decisions.

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

BM: Writing – original draft, Writing – review and editing. JG: Conceptualization, Formal Analysis, Resources, Writing – original draft. PC: Investigation, Methodology, Supervision, Writing – original draft. LZ: Funding acquisition, Writing – original draft. HW: Validation, Writing – original draft. YZ: Data curation, Formal Analysis, Writing – original draft. BS: Data curation, Validation, Writing – original draft.

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Conflict of interest

Authors BM, JG, PC, and LZ were employed by PowerChina Huadong Engineering Corporation Limited.

The remaining 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/feart.2025.1645693/full#supplementary-material

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Perception of and adaption to climate change: the case of groundnut production of costal island in Bangladesh

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Introduction: Nut farming in the island regions of Bangladesh faces considerable challenges due to climate change. This research investigates the climate change perceptions and adaptive capacity of strategies of male and female groundnut farmers in island of Hatiya, Bangladesh where nut yields fall below the national average.
Methods: Data were gathered from 170 male and 130 female farmers on the island, with Chi-square tests used to analyze gender-based differences in perceptions of climate change and adaptive capacity. A probit regression model was applied to evaluate the factors driving the adoption of these strategies.
Results and discussion: The findings suggest that male and female farmers largely share similar perceptions of climate change impacts, such as changes in rainfall patterns, increased pest infestations, and a greater need for fertilizers. Consequently, a combined analysis of both genders was conducted to identify the factors influencing adaptive capacity of strategies. Additionally, the results indicated that older farmers are more likely to engage in off-farm activities as a strategy to cope with environmental uncertainties. Education and farming experience are key factors in driving crop diversification and climate-smart practices, with farmers adjusting planting dates, shifting crops, and using weather forecasts as the most common adaptive capacity. Less frequently adopted strategies include agroforestry and urban migration. Education and farming experience are positively associated with the adoption of proactive adaptive capacity, thereby improving farmers' ability to cope with climate change. This study exploring adaptive capacity of nut farmers in Bangladesh's island and suggests interventions to enhance resilience and encourage sustainable agricultural practices in response to climate change.

KEYWORDS

nut production, island, adaptive capacity, climate change, sustainable agriculture

1 Background

The landscape of Bangladesh is defined by numerous islands, estuaries, and riverine areas, where agricultural practices and land use are influenced by the dynamic interaction between land and water. The country's geographical features include many islands, particularly in the coastal regions (Mosa et al., 2023). These islands, often referred to as chars or sandbars, are constantly reshaped by river and tidal movements, making them both fertile and challenging for agriculture. Bangladesh's agrarian economy is highly dependent on its riverine and island ecosystems, where agriculture remains the mainstay for millions of rural households (Chowdhury, 2021).

Hatiya Island is one such significant island located in the southern part of Bangladesh, in the Noakhali District. The island is part of the Chattogram Division, situated in the Bay of Bengal's coastal belt. Hatiya is one of the largest islands in Bangladesh and is surrounded by the Bay of Bengal and other rivers (Uddin et al., 2022). The island is subject to the challenges of salinity, flooding, and soil erosion, which significantly affect the livelihood of its inhabitants (Roy et al., 2024). Despite these challenges, Hatiya continues to have significant agricultural potential, especially in crop cultivation and livestock farming. The people of Hatiya largely depend on agriculture for their livelihood, with nut farming especially the cultivation of coconut, betel nut, and date palm being a key component of the local economy (Shahidullah et al., 2006). These crops, which thrive in the tropical climate of the island, have become an integral part of the agricultural landscape, not only providing food and income to the farmers but also offering significant cultural and economic value (Dagar, 1995; Pawlak and Kołodziejczak, 2020). The island's agricultural productivity is threatened by climate change, particularly rising sea levels, increased salinity, and the frequent occurrence of natural disasters such as cyclones and floods (Roy et al., 2022). However, the farming communities on Hatiya Island face numerous socio-economic challenges. These include issues such as low income, poor infrastructure, and limited access to credit and markets, land erosion, which make it difficult for farmers to improve their living standards (Rahman and Rahman, 2015). These factors have intensified the vulnerability of farming communities, particularly in the production of crops that rely on favorable climatic conditions. Farmers' perceptions of these environmental challenges, as well as the perceived impacts on their agricultural productivity and socio-economic well-being, are critical for understanding how they respond to such challenges (Jha and Gupta, 2021). Thus, understanding the socio-economic conditions, perceptions of climate change impacts, and adaptive capacity of strategies of farmers in Hatiya Island is essential for developing sustainable agricultural policies and support programs. Climate change refers to long-term and persistent changes in climate patterns, particularly variations in temperature, rainfall, and the frequency of extreme weather events whereas adaptive capacity is the ability of farmers to adjust, mitigate, and recover from the adverse impacts of climate change through the utilization of available resources, knowledge, and skills.

Groundnut (peanut) is a key crop in Bangladesh, especially in the northern and central regions, where the climate and soil conditions favor its growth (Deb and Pramanik, 2015). It is valued for its nutritional content and versatility in food, oil production, and export markets. Peanut oil, rich in unsaturated fatty acids and oleic acid, offers health benefits, such as improved cardiovascular health, reduced LDL oxidation, and lower risk of type 2 diabetes. Groundnut and its products also help reduce the risk of colorectal cancer. Groundnut farming plays a crucial role in food security and income generation, particularly for smallholder farmers (Suchoszek-Łukaniuk et al., 2011). In this study, groundnut farmers are predominantly smallholders, cultivating from 0.1 to 2 hectares of land. They typically operate at a subsistence or semi-commercial level, with limited access to capital, agricultural technology, and extension services. On Hatiya Island, groundnut cultivation has grown due to favorable soil types and low input requirements, significantly contributing to the local economy (Melesse et al., 2023). Despite challenges such as climate related issues and market fluctuations, groundnut farming continues to thrive on the island, helping to enhance agricultural diversity and resilience in the region.

Over the period from the financial year 2013–2014 to 2022–2023, Smallholder nut farmer's in Bangladesh consistently outpaced that on Hatiya Island, though the gap between the two fluctuated. In the early years, such as 2013–2014, national production was significantly higher at 1.89 million metric tons, compared to 1.57 million metric tons on the island, resulting in a difference of 0.32 million metric tons. However, from 2018 to 2020, the gap narrowed considerably, with national and island production almost identical, differing by just 0.01 million metric tons. In the later years, such as 2020–2021 and 2021–2022 (Figure 1), the disparity remained small, with national production hovering between 1.85 and 1.91 million metric tons, and island production fluctuating between 1.80 and 1.85 million metric tons. While Hatiya Island has seen significant groundnut production, it remains notably lower than in previous years, largely due to the impact of climate change. Fluctuating environmental conditions have led to a decline in yields compared to earlier years. This decrease highlights the challenges island farmers face in maintaining stable production amid changing climate patterns. The disparity in production levels emphasizes the need for adaptive strategies to address the environmental impacts and sustain groundnut farming on the island.

Farmers' perceptions of climate change and their subsequent adaptation strategies are crucial to understand the broader impacts of climate variability on agriculture. Numerous studies have explored how farmers in different regions perceive climate change and the factors influencing their adaptive responses. Datta et al. (2022) conducted a systematic review of Indian farmers' perceptions and adaptation strategies, emphasizing the importance of localized approaches to coping with climate change. Similarly, Ricart et al. (2023) reviewed farmers' awareness of climate change and their behavioral adaptations, highlighting the role of experience in shaping responses. Jha and Gupta (2021) also examined the factors influencing adaptation decisions among Indian farmers, underlining socio-economic factors and institutional support as key determinants. Farmers' perceptions of climate change significantly influence their adaptation strategies, as highlighted in studies by Moniruzzaman et al. (2023) and Tasnim et al. (2023), which examine wheat farmers in Bangladesh. Studies in other countries have provided further insights, such as Yang et al. (2021), explored livestock farmers' perceptions in China, and Balasha et al. (2023), focused on adaptation practices in the marshlands of the Democratic Republic of Congo. Smallholder farmers' adaptation strategies were shaped by their perceptions of climate change, with significant differences observed between agro-ecological zones in Ghana (Aidoo et al., 2021; Adeboa and Anang, 2024). These findings highlight the importance of understanding farmers' perceptions and contextual factors to develop effective climate change strategies.

While much research has explored the broader impacts of climate change on agriculture in Bangladesh, most studies concentrate on major cereal crops in mainland areas and overlook cash crops like groundnut, which are vital for this coastal livelihood and highly sensitive to climatic changes due to distinct agro-ecological conditions like tidal flooding, soil salinity, land erosion, and isolation from extension services all of which uniquely influence farmers' adaptive behavior. Unlike previous studies, this research also explores gender

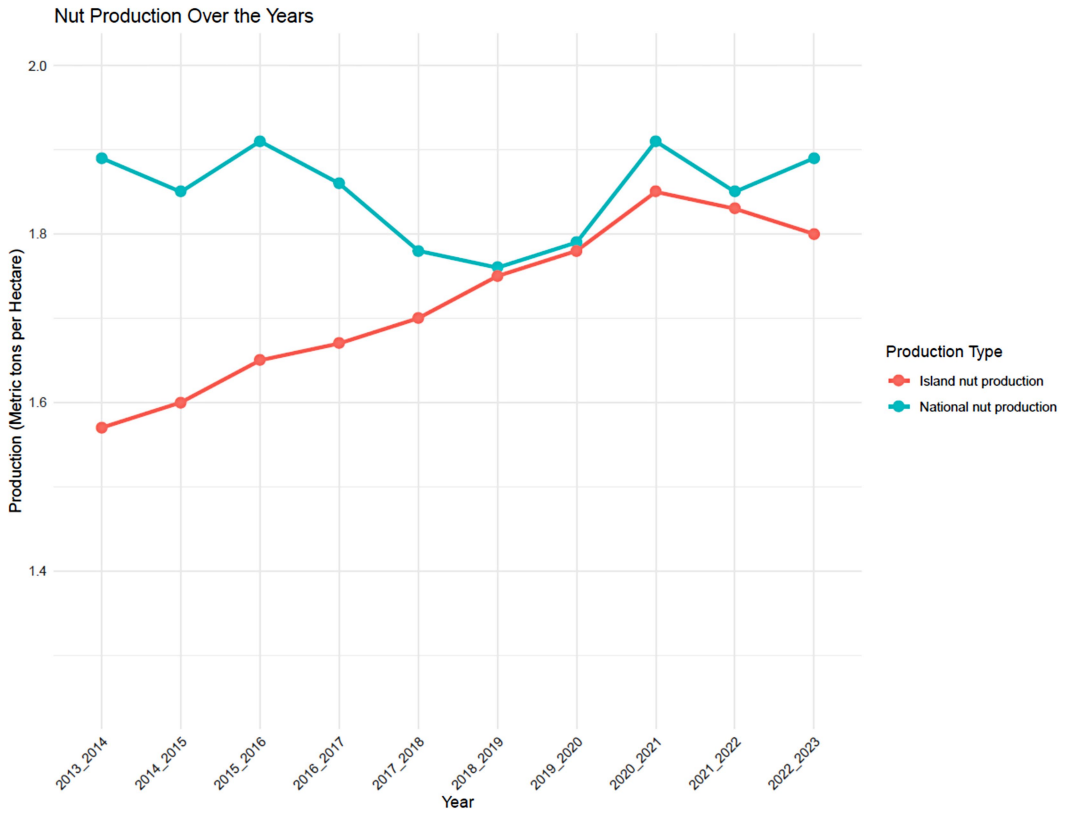


FIGURE 1
Production scenario of nut production in national and Hatiya island of Bangladesh.

differences in perceptions and adaptation behaviors, specifically how male and female farmers respond to climate change.

The main research gap addressed by this study lies in the lack of comprehensive understanding of the socioeconomic factors that influence the adaptive capacity of strategies of groundnut farmers. This research focuses on the production disparities between Hatiya Island and national levels, addressing a critical gap by examining how socioeconomic factors such as training, education, farming experience, and access to subsidies affect the adaptive capacity of groundnut farmers in an island context.

By focusing on groundnut farmers in the coastal island of Hatiya, this study provides new insights into the intersection of climate change, socioeconomics, and gender in a marginalized and under-researched geographic setting, offering both theoretical contributions and practical recommendations for climate-resilient agricultural planning.

2 Methodology

2.1 Study area and data

The study was conducted to explore groundnut farmers' perceptions and adaptations to climate change in Bangladesh's climate-vulnerable coastal island. It focused on Hatiya Island, which is frequently exposed to climatic hazards such as cyclones, tidal surges, saltwater intrusion, and erratic rainfall patterns that threaten agricultural productivity. The island's farming population is predominantly composed of smallholder farmers with limited access to education, extension services, and climate information, making them particularly vulnerable. Hatiya Island, is a key area for groundnut production and was purposively chosen for the study due to its significant role in local production (Figure 2). In the fiscal year 2022–2023, the total cultivated area for groundnut farming in Bangladesh was estimated at 97,875 acres, with the Noakhali region accounting for approximately 17,893 acres (18.28%) (Bangladesh Bureau of Statistics (BBS), 2024). A total of 300 groundnut farmers where 170 male and 130 female groundnut farmers were selected from the list provided by the Upazila Agriculture Offices through simple random sampling technique. Data collection occurred during the groundnut harvest season, from February to May (2022–2023), with face-to-face interviews conducted using a structured interview schedule in Tomoruddin, Burirchor, Jahajmara, Chorking, and Nijumdwip region. This schedule was designed after an extensive literature review and included questions on farmers' perceptions of climate variability, the causes and impacts of climate change, adaptive capacity of strategies, factors affecting adaptive capacity, and their socioeconomic characteristics. Prior to the main survey, a pilot test was conducted with a few farmers in the study area, and the interview schedule was adjusted based on the feedback to ensure it met the study objectives.

2.2 Analysis of data

Descriptive statistics were used to summarize the socioeconomic characteristics of the farmers in the study. Frequencies and percentages

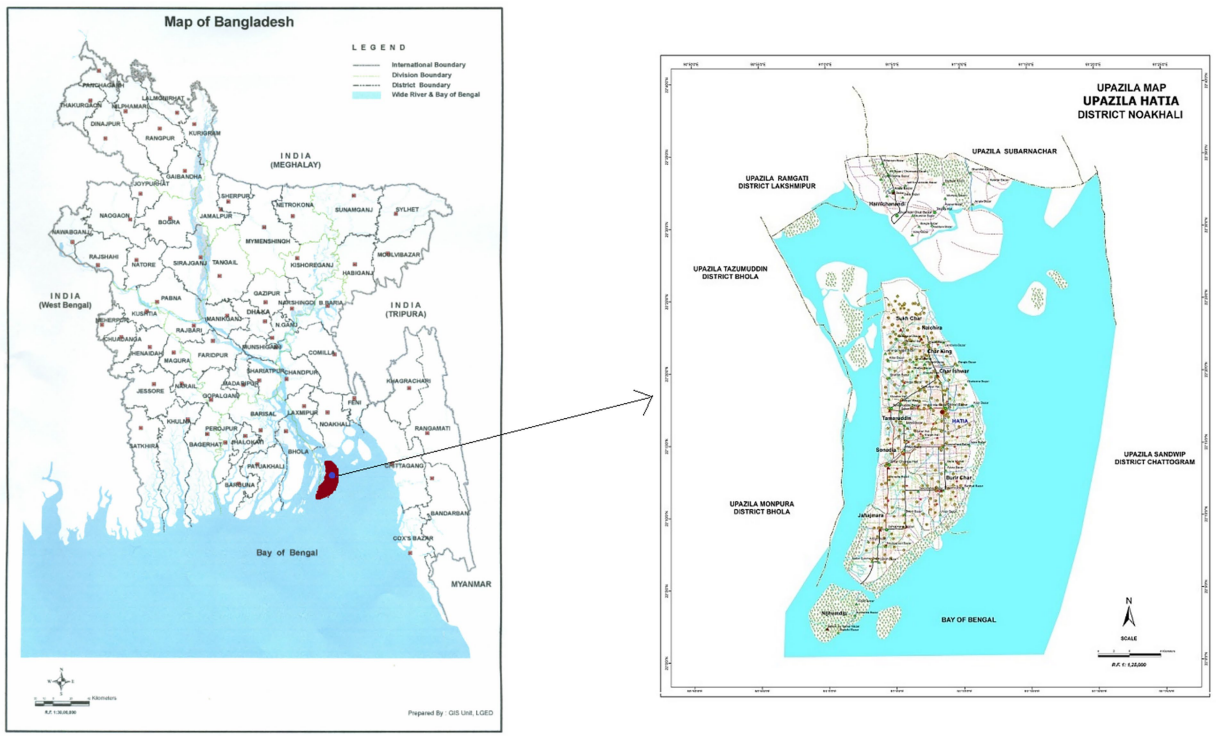


FIGURE 2
Selected study area.

were calculated for categorical variables, while the mean, standard deviation, minimum, and maximum values were computed for continuous variables, such as contact with extension agents, training days, farm size, and annual income. These analyses were performed using R software to provide a comprehensive overview of the study participants' profiles.

To examine the differences in perceptions, perceived impacts, and adaptive capacity between male and female farmers, a Chi-square test was conducted using R software. The Chi-square test was used to assess whether gender differences exist in the perceptions of climate change and the adoption of strategies. This test is particularly suitable for categorical data and allowed us to identify whether the observed gender differences were statistically significant.

2.2.1 Relationships between socio-economic factors and adaptive capacity of strategies

In this study, a multivariate probit regression model was employed to assess the relationships between adaptive capacity of strategies and socio-economic factors (Henningsen, 2021). The multivariate probit model was selected because it allows us to analyze the simultaneous adoption of multiple adaptation capacity (binary outcomes) and account for potential correlations between them. For instance, a farmer may adopt several strategies (e.g., adjusting planting dates and diversifying crops) in response to climate change. The model was specified using the mvProbit function in R, with the dependent variables representing different adaptive capacity, including changes in planting and harvesting dates, shifts to other crops, adoption of agroforestry and horticultural practices, migration to urban areas, use of weather forecasts, and shifts to other crop varieties. These strategies were modeled as binary outcomes, indicating whether a household had adopted each respective strategy. The independent variables included socio-economic factors such as sex, age, household size, access to credit, access to input subsidies, training received, contact with extension agents, farm size (in hectares), access to climate information, years of education, and years of farming experience. This approach allowed for the simultaneous analysis of multiple interrelated decisions made by households in response to environmental or socio-economic stressors, thus providing a more comprehensive understanding of the factors influencing adaptive capacity. Multicollinearity among predictors was checked using variance inflation factors (VIF), all within acceptable limits.

After running the multivariate probit regression model using the mvProbit function in R, we examined the estimated coefficients, standard errors, and *p*-values for each of the predictor variables. The estimated coefficients represent the change in the log-odds of adopting a particular adaptation strategy for a one-unit change in the respective independent variable, holding all other variables constant. A positive coefficient indicates that an increase in the predictor variable is associated with a higher likelihood of adopting the corresponding adaptation strategy, while a negative coefficient suggests the opposite. The standard errors reflect the precision of the coefficient estimates. Smaller standard errors indicate more precise estimates, while larger standard errors suggest greater uncertainty about the coefficient values. The *p*-values were used to assess the statistical significance of each predictor variable. A p-value less than 0.10 were considered evidence that the predictor variable significantly influences the likelihood of adopting a particular adaptation strategy.

2.2.2 Predicted probability and correlation analysis of key factors

After fitting the multivariate probit regression model, predicted probabilities for each adaptation strategy were calculated to assess the likelihood of households adopting specific strategies based on their socio-economic characteristics. Using the mvProbit function in R, we generated predicted probabilities for each binary adaptation strategy (e.g., changes in planting and harvesting dates, shifts to other crops, agroforestry adoption, migration, and use of weather forecasts). These probabilities were computed by applying the estimated coefficients from the probit model to the observed values of the independent variables (such as sex, age, household size, education, and farming experience) for each household. The predict () function with the type = "response" argument was used to obtain the predicted probabilities, which represent the likelihood of adopting each strategy, with values ranging from 0 to 1. These predicted probabilities were then examined for each adaptation strategy, providing insights into the factors that influence the likelihood of households engaging in various adaptive behaviors in response to environmental or socio-economic stressors.

To further explore the relationship between the predicted probabilities and key socio-economic factors, we visualized the correlation between predicted probabilities and key socio-economic factors using ggplot2. Scatter plots were created to examine how these socio-economic variables influence the likelihood of adopting each adaptation strategy. The geom_point() function was used to plot the predicted probabilities against education and farming experience, while geom_smooth() was applied to add trend lines that help visualize the strength and direction of the relationships.

3 Results and discussions

3.1 Socio-economic characteristics of nut farmers

The study sample consists of 170 males (56.67%) and 130 females (43.33%), with a predominant age group of 15–35 years (66%), followed by participants aged 36–50 years (22.33%) and those older than 50 years (11.67%). The average household size among the farmers was 5.67 members, which is slightly higher than the national average, indicating a relatively larger family structure compared to the general population (Bangladesh Bureau of Statistics (BBS), 2024). The majority of respondents are engaged in agriculture (89.33%). In terms of education, 45.33% have completed Junior High School (JHS) or middle school, followed by 38.33% with primary education, and 16.33% with Senior High School (SHS) or A-level education. The average educational level of nut farmers on coastal islands is lower compared to the national average (Bangladesh Bureau of Statistics (BBS), 2024), reflecting disparities in access to education between remote agricultural areas and urban regions. When it comes to farming experience, 41% of participants have 11 to 20 years of experience, with smaller groups having 0–10 years (34.33%) or 21–30 years (24.67%) of farming experience. The average contact with extension agents is limited, with a mean of 1.21 days, and participants have received an average of 1.08 days of training. Farm sizes are generally small, with the average farm size being 0.47 hectares (SD = 0.31), and annual incomes range from 75,000 to 200,000 TK (Bangladeshi currency). This data highlights a predominance of younger, male, and agriculture-based participants with relatively low levels of formal education, modest farm sizes, and limited engagement with extension services and training programs (Table 1).

3.2 Smallholder nut farmers' perception of climate change

Understanding the perceptions of climate changes is crucial for developing targeted adaptive capacity of adaption strategies. Table 2 presents smallholder nut farmers' perceptions of changes in rainfall timing and distribution over the past decade (2014–2023). On the topic of increased rainfall, 28% of males and 21.66% of females agreed, with a higher proportion of males being neutral (18%) compared to females (14.66%). Conversely, for decreased rainfall, 26% of males disagreed, compared to 18% of females, indicating a stronger perception of decreased rainfall among men. When asked about the late onset of rains, a similar trend emerged, with 24% of males and 20% of females disagreeing, suggesting a common perception across genders. Case of the early onset of rains, a significant gender difference was observed, with 30.33% of males and 23.33% of females agreeing to the statement, and this difference is statistically significant (p-value<0.0001). For the late end of rains, 25.66% of males and 21% of females agreed, but the chi-square test showed no significant difference (p-value = 0.4888). The perception of poor distribution of rainfall also revealed a noteworthy gender difference, with 32.33% of males and 21.66% of females agreeing, and this difference was statistically significant (p-value = 0.03339). Male farmers, in particular, were reported to perceive themselves as more vulnerable to changes in rainfall patterns and the growing season (Bessah et al., 2021). This aligns with the current findings, where gender-based variations in the perception of climate variability are evident. The gender differences in perceptions of rainfall changes on Hatiya Island can be attributed to factors such as differing access to resources and information, gender roles in farming, and varying responsibilities.

Overall, while there are some common perceptions between males and females regarding rainfall patterns, significant gender-based differences are particularly evident in the early onset and poor distribution of rainfall, where males tended to have stronger agreement.

The data presented in Table 3 reflects the perceptions of male and female respondents regarding various weather risks for a decade (2014–2023). Regarding increased temperature, 29.66% of males and 23.66% of females agreed that temperatures were rising, with almost similar proportion of both genders being neutral 13.66% of males and 11.66% of females although the difference was not statistically significant ($\chi^2 = 0.5525$). When asked about cold wave severity, 30.33% of males and 25.66% of females agreed that cold waves were becoming more severe, with males also showing slightly higher disagreement (15%) compared to females (9.33%). Again, this difference was not statistically significant ($\chi^2 = 0.5526$). For hot wave severity, a majority of both genders agreed, with 33.66% of males and 28.33% of females acknowledging the increased severity, though the difference was not statistically significant ($\chi^2 = 0.4644$). On the topic of climate change intensity, 27% of males and 23.33% of females considered the changes "intense." Overall, more males (18.33%) reported a perception of no change compared to females (11.33%), but again, the chi-square test showed no significant difference

TABLE 1 Socio-economic characteristics of the respondents.

Variable	Categories	Frequency	Percentage	Mean	SD	Min	Max
Gender	Male	170	56.67				
	Female	130	43.33				
Age (years)	15–35	198	66.00	28.37	5.57	15	35
	36–50	67	22.33	44.14	3.07	36	50
	>50	35	11.67	54.68	4.40	51	56
Household size	2 to 6	203	67.67	4.56	1.24	2	6
	7 to 10	97	32.33	7.97	1.02	7	10
Occupation	Agriculture	268	89.33				
	Fish farmer	17	5.67				
	Service	15	5.00				
Education (years)	Primary	115	38.33				
	JHS/Middle School	136	45.33				
	SHS/O/A Level	49	16.33				
Farming experience (years)	0–10	103	34.33	5.32	3.36	0	10
	11 to 20	123	41.00	15.60	2.68	11	20
	21–30	74	24.67	25.58	2.94	21	30
Contact with extension agents (days)				1.21	1.21	0	4
Training (days)				1.08	1.09	0	3
Farm size (hector)				0.47	0.31	0.1	2
Annual income (TK.)				164616.67	44636.43	75,000	200,000

($\chi^2 = 0.4684$). Bessah et al. (2021) demonstrated significant differences in how climate change is perceived and addressed by male and female farmers. For instance, male farmers were found to perceive themselves as more vulnerable to increased temperatures during the growing season. This aligns with the findings in the current study. These findings suggest that while there are slight differences in perception between males and females regarding various weather risks, the overall patterns are similar across both groups, and no significant gender-based differences were observed in the statistical analysis. Kumar et al. (2022) found that there is no significant difference in the knowledge and understanding of climate change between adult male and female respondents.

Table 4 outlines the perceptions of male and female nut farmers regarding the causes of climate change. The data reveals notable gender differences in the perceived drivers of climate change. Regarding environmental factors, 14% of male farmers and 8% of female farmers agreed that environmental factors contribute to climate change, with a statistically significant difference ($\chi^2 = 0.001938$), indicating that male farmers are more likely to perceive environmental factors as a primary cause. Denton highlights that gender can influence the understanding and attribution of climate change, with men often focusing more on environmental causes, while women may consider a broader range of factors (Denton, 2002). In contrast, supernatural factors were perceived by 15.33% of males and 20% of females, with females exhibiting a stronger belief in supernatural causes of climate change. Female farmers often expressed these views with statements such as Fatima, a smallholder nut farmer, who said, "Sometimes, the changes in weather feel like a punishment from unseen forces." Similarly, Rina shared, "Some say the gods are angry with the way we live now." Shahana added, "If the rain stops suddenly, it is because someone did not respect the sacred places nearby." These quotes illustrate how cultural and spiritual beliefs influence perceptions of climate variability among women farmers. For human activities, 10.66% of males and 5% of females attributed climate change to human actions, suggesting that males tend to emphasize human responsibility more than females. Both male and female farmers reported similar perceptions of political factors, with 6% of males and 6.33% of females agreeing, and no significant gender differences were observed. Lastly, 10.66% of males and 4% of females reported having no knowledge of climate change causes, with males more likely to express uncertainty.

Several studies have explored gender differences in the perception of environmental issues and climate change, which can help contextualize the finding that male farmers are more likely to perceive environmental factors as a primary cause of climate change. Agarwal (1992) discusses how men and women in rural and agricultural communities may prioritize different environmental factors due to their distinct roles in agricultural practices and land management. This supports the idea that male farmers, with greater involvement in direct environmental management, may be more attuned to environmental changes. Additionally, it was also suggest that perceptions of climate change and its environmental drivers are shaped by the roles individuals play in agriculture, which can vary by gender (Haque et al.,

TABLE 2 Perceived changes in rainfall timing and distribution among smallholder nut farmers (2014–2023).

Rainfall pattern	Perception	Male	Female	Total	χ^2 *p*-value
Increased rainfall	Agree	84 (28%)	65 (21.66%)	149 (49.66%)	0.8187
	Neutral	54 (18%)	44 (14.66%)	98 (32.66%)	
	Disagree	32 (10.66%)	21 (7%)	53 (17.66%)	
	Total	170 (56.67%)	130 (43.33%)	300 (100%)	
Decreased rainfall	Agree	35 (11.66%)	31 (10.33%)	66 (22%)	0.7058
	Disagree	78 (26%)	54 (18%)	132 (44%)	
	Neutral	57 (19%)	45 (15%)	102 (34%)	
	Total	170 (56.67%)	130 (43.33%)	300 (100%)	
Late onset of rains	Agree	48 (16%)	27 (9%)	75 (25%)	0.3323
	Disagree	72 (24%)	60 (20%)	132 (44%)	
	Neutral	50 (16.66%)	43 (14.33%)	93 (31%)	
	Total	170 (56.67%)	130 (43.33%)	300 (100%)	
Late end of rains	Agree	77 (25.66%)	63 (21%)	140 (46.66%)	0.4888
	Disagree	51 (17%)	31 (10.33%)	82 (27.33%)	
	Neutral	42 (14%)	36 (12%)	78 (26%)	
	Total	170 (56.67%)	130 (43.33%)	300 (100%)	
Early onset of rains	Agree	91 (30.33%)	70 (23.33%)	161 (53.66%)	0.00005
	Disagree	64 (21.33%)	27 (9%)	91 (30.33%)	
	Neutral	15 (5%)	33 (11%)	48 (16%)	
	Total	170 (56.67%)	130 (43.33%)	300 (100%)	
Early end of rains	Agree	39(%)	26 (8.66%)	65 (21.66%)	0.5111
	Disagree	71(%)	63 (21%)	134 (44.66%)	
	Neutral	60(%)	41 (13.66%)	101 (33.66%)	
	Total	170 (56.67%)	130 (43.33%)	300 (100%)	
Poor distribution of rainfall	Agree	97 (32.33%)	65 (21.66%)	162 (54%)	0.03339
	Disagree	52 (17.33%)	34 (11.33%)	86 (28.66%)	
	Neutral	21 (7%)	31 (10.33%)	52 (17.33%)	
	Total	170 (56.67%)	130 (43.33%)	300 (100%)	

2023). This notion is further supported by Maya Moore et al., who propose that gender influences the way farmers interpret and respond to climate change, with female farmers are significantly vulnerabilities to climate change (Moore and Niles, 2025). Furthermore, male farmers are more likely to attribute climate change to environmental factors, reflecting a deeper awareness of environmental degradation and its impact on agriculture (Food and Agriculture Organization of the United Nations, 2016; Sheikh et al., 2024). These findings suggest that male and female nut farmers have varying perceptions of the factors contributing to climate change, with significant differences observed in their views on environmental factors and supernatural factors, but no major gender-based differences in other categories.

3.3 Perceived impacts of climate change on nut farming

Table 5 presents the perceived impacts of climate change on nut farming, comparing the responses of male and female farmers. The data reveals that both male and female farmers perceive similar climate-related challenges, with only minor gender differences observed across various impacts.

Regarding changes in the timing of rain, 34.33% of male farmers and 23.66% of female farmers agreed that rainfall patterns have shifted, which is not significant indicates that there is no significant gender difference in this perception. Nnadi et al. (2019) found significant gender differences in the perception of rainfall variability in Anambra, Southeast Nigeria, with female farmers possibly perceiving rainfall changes differently than their male counterparts. Similarly, for increased plant diseases, 32.33% of males and 27% of females agreed which is insignificant. For increased pest infestations, 37% of male farmers and 26.33% of female farmers agreed that pests have become a bigger problem. One of the most important predictors of the magnitude of climate change effects may be the adaptive potential of plant and pathogen populations (Garrett et al., 2006). Gender perceptions regarding changes in the prevalence of pests can provide valuable insights that contribute to the sustainable development of smallholder irrigation farming systems. Understanding how different genders perceive pest-related challenges can help inform targeted strategies and policies that enhance resilience

TABLE 3 Perceptions of weather risks among smallholder nut farmers (2014–2023).

Weather risk	Perception	Male	Female	Total	χ^2 *p*-value
Increased temperature	Agree	89 (29.66%)	71 (23.66%)	160 (53.33%)	0.5525
	Disagree	40 (13.33%)	24 (8%)	64 (21.33%)	
	Neutral	41 (13.66%)	35 (11.66%)	76 (25.33%)	
	Total	170 (56.67%)	130 (43.33%)	300 (100%)	
Cold wave severity	Agree	91 (30.33%)	77 (25.66%)	168 (56%)	0.5526
	Disagree	45 (15%)	28 (9.33%)	73 (24.33%)	
	Neutral	34 (11.33%)	25 (8.33%)	59 (19.66%)	
	Total	170 (56.67%)	130 (43.33%)	300 (100%)	
Hot wave severity	Agree	101 (33.66%)	85 (28.33%)	186 (62%)	0.4644
	Disagree	35 (11.66%)	20 (6.66%)	55 (18.33%)	
	Neutral	34 (11.33%)	25 (8.33%)	59 (19.66%)	
	Total	170 (56.67%)	130 (43.33%)	300 (100%)	
Climate change intensity	Very Intense	55 (18.33%)	34 (11.33%)	89 (29.66%)	0.4684
	Intense	81 (27%)	70 (23.33%)	151 (50.33%)	
	No Change	34 (11.33%)	26 (8.66%)	60 (20%)	
	Total	170 (56.67%)	130 (43.33%)	300 (100%)	

TABLE 4 Smallholder nut farmers' perceptions of climate change causes (2014–2023).

Perception	Male	Female	Total	χ^2 *p*-value
Environmental factors	42 (14%)	24 (8%)	66 (22%)	0.0019
Supernatural factors	46 (15.33%)	60 (20%)	106 (35.33%)	
Human activities	32 (10.66%)	15 (5%)	47 (15.66%)	
Political factors	18 (6%)	19 (6.33%)	37 (12.33%)	
No knowledge	32 (10.66%)	12 (4%)	44 (14.66%)	
Total	170 (56.67%)	130 (43.33%)	300 (100%)	

and productivity within these agricultural systems (Mwadzingeni et al., 2022). The finding that 39% of male farmers and 27% of female farmers agreed on the increased requirement for fertilizers, which is consistent with study Islam et al. (2023) found that fertilizer use rates in women-headed households (WHHs) varied with crop type and cropping patterns, highlighting the gender-based differences in fertilizer application. This aligns with our result, where male farmers and female farmers agreed on the increased requirement for fertilizers. Regarding crop loss, 31% of male farmers and 26.33% of female farmers agreed that climate change has led to increased crop loss, accounting for a total of 57.33% of respondents. The chi-square test ($p = 0.3501$) indicates no statistically significant difference between male and female perceptions on this issue. In terms of the disturbance of the agricultural calendar, 43.66% of male farmers and 32.66% of female farmers agreed that climate change has disrupted their farming schedules. Finally, for decline of soil fertility, 33% of male farmers and 28.33% of female farmers agreed that soil fertility has declined. Balasha et al. observed that farmers consistently faced challenges related to declining soil fertility and crop loss (Balasha et al., 2023), which aligns with the impacts of climate change reported by farmers in our study. Overall, the findings suggest that male and female nut farmers share similar perceptions regarding the impacts of climate change on their farming practices, with no significant gender differences.

Moreover, the results indicated differences in the perceptions of agricultural changes between male and female participants (Figure 3). Both groups agreed on several issues, but males generally showed a higher level of agreement across most perceptions. For instance, a higher percentage of males (34.33%) agreed that the timing of rain has changed, compared to females (23.66%). Similarly, males reported greater concern about increased plant diseases (32.33% vs. 27%), pest infestations (37% vs. 26.33%), and the increased need for fertilizers (39% vs. 27%). Males also perceived greater crop loss (31% vs. 26.33%) and more disturbances in the agricultural calendar (43.66% vs. 32.66%). The decline in soil fertility was similarly perceived by more males (33%) than females (28.33%).

Overall, while both male and female participants shared similar concerns, males appeared to have a stronger perception of the agricultural challenges. The differences in agricultural perceptions between men and women are likely due to men's greater involvement in decision-making and large-scale farming, better access to climate information and extension services, education, and a stronger focus on economic impacts (Carnegie et al., 2020; Nchanji et al., 2025). Cultural norms and gender roles may also influence how concerns are expressed, with men more likely to report broader agricultural challenges (Holmelin, 2019; Mudege et al., 2017). These factors contribute to men's heightened perception of agricultural issues.

TABLE 5 Perceived impacts of climate change on nut farming (2014–2023): gender differences in farmers' perspectives.

Perceived impacts	Perception	Male	Female	Total	χ^2 *p*-value
Changes in the timing of rain	Agree	103 (34.33%)	71 (23.66%)	174 (58%)	0.3572
	Disagree	67 (22.33%)	59 (19.66%)	126 (42%)	
	Total	170 (56.66%)	130 (43.33%)	300 (100%)	
Increased plant diseases	Agree	97 (32.33%)	81 (27%)	178 (59.33%)	0.4246
	Disagree	73(%24.33)	49 (16.33%)	122 (40.66%)	
	Total	170 (56.66%)	130 (43.33%)	300 (100%)	
Increased pest infestations	Agree	111 (37%)	79 (26.33%)	190 (63.33%)	0.4933
	Disagree	59 (19.66%)	51 (17%)	110 (36.66%)	
	Total	170 (56.66%)	130 (43.33%)	300 (100%)	
Increased requirement of fertilizers	Agree	117 (39%)	81 (27%)	198 (66%)	0.2902
	Disagree	53 (17.66%)	49 (16.33%)	102 (34%)	
	Total	170 (56.66%)	130 (43.33%)	300 (100%)	
Crop Loss	Agree	93 (31%)	79 (26.33%)	172 (57.33%)	0.3501
	Disagree	77 (25.66%)	51 (17%)	128 (42.66%)	
	Total	170 (56.66%)	130 (43.33%)	300 (100%)	
Disturbance of agricultural calendar	Agree	131 (43.66%)	98 (32.66%)	229 (76.33%)	0.8407
	Disagree	39 (13%)	32 (10.66%)	71 (23.66%)	
	Total	170 (56.66%)	130 (43.33%)	300 (100%)	
Decline of soil fertility	Agree	99 (33%)	85 (28.33%)	184 (61.33%)	0.2541
	Disagree	71 (23.66%)	45 (15%)	116 (38.66%)	
	Total	170 (56.66%)	130 (43.33%)	300 (100%)	

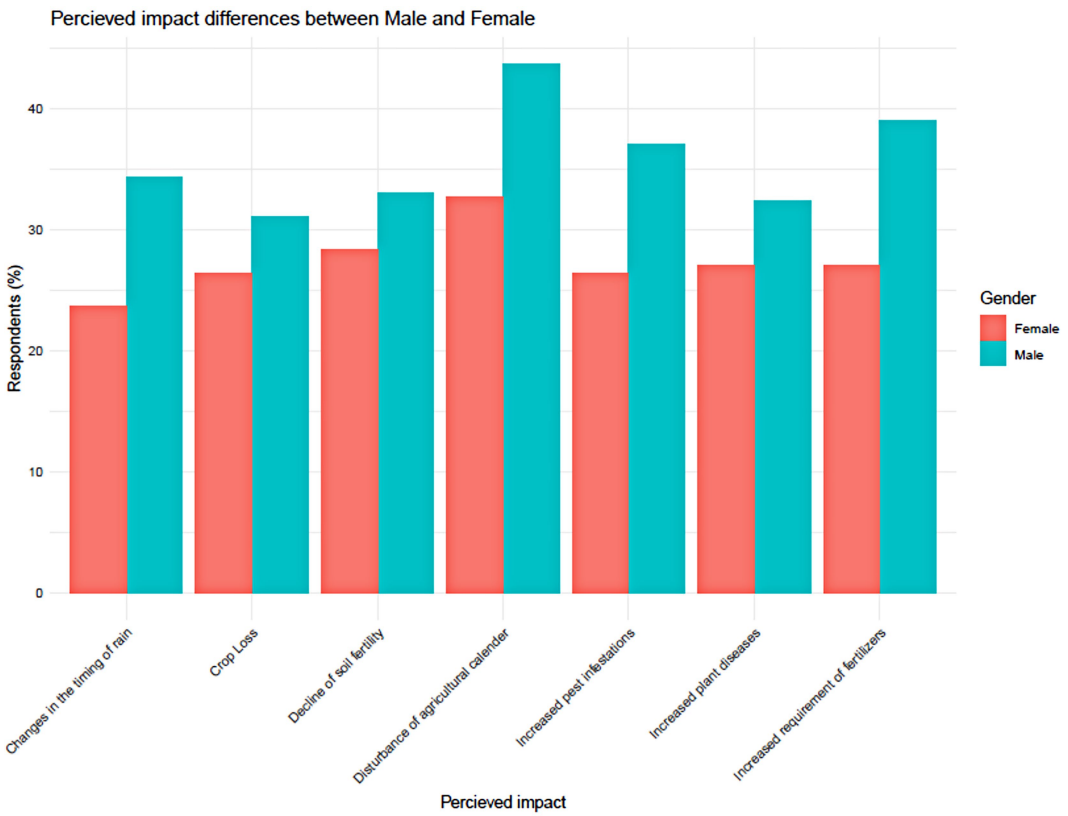


FIGURE 3
Gender-based comparison of perceived impacts on agricultural changes and challenges.

3.4 Adaptive capacity of strategies taken by farmers

In response to the challenges posed by changing climate patterns and environmental variability, farmers have adapted a range of strategies to sustain their livelihoods and improve resilience. The results of the Pearson's Chi-squared tests on adaptive capacity of strategies showed a significant gender-based difference in only one response (Figure 4). Males (118 "Yes" responses) were more likely than females (75 "Yes" responses) to report changing planting and harvesting dates ($p < 0.05$). In contrast, no significant gender differences were observed for the other strategies.

To assess potential gender differences in response to climate change, the adoption of various strategies by farmers was analyzed. These strategies, which include changing agricultural practices, diversifying income sources, and utilizing climate-related information, reflect farmers' efforts to cope with the challenges posed by climate change (Figure 4). For changing planting and harvesting dates, Males (118 "Yes" responses) were more likely than females (75 "Yes" responses) to report changing their planting and harvesting dates (Figure 4), with a statistically significant difference observed ($p < 0.0479$). In contrast, for strategies such as shifting to other crops, Males (114 "Yes" responses) and females (80 "Yes" responses) showed no significant difference ($p > 0.05$) (Figure 4). Similarly, shifting to agroforestry and horticultural crops had nearly equal responses from males (76 "Yes") and females (58 "Yes"), with no significant gender difference ($p > 0.05$) (Figure 4). The adoption of off-farm income was also similar between males (96 "Yes") and females (80 "Yes"), with no significant difference ($p > 0.05$) (Figure 4). The responses for migration to urban areas (Males: 81 "Yes," Females: 67 "Yes") and the use of weather forecasts (Males: 114 "Yes," Females: 93 "Yes") did not reveal significant gender differences either ($p > 0.05$) (Figure 4). Finally, for shifting to other crop varieties, Males (94 "Yes") and females (80 "Yes") again exhibited no significant difference in adoption ($p > 0.05$) (Figure 4). Overall, the results indicate that while there is a significant gender difference in the adoption of changing planting and harvesting dates, other strategy were equally adopted by both male and female farmers. The gender difference in responses could reflect social and cultural factors, where men might be more active in making visible, larger-scale changes on the farm. However, the overall similarity in other responses suggests shared experiences and challenges across both genders. Several studies have explored the influence of gender on agricultural adaptive capacity, supporting the findings observed in our study. Doss and Morris explore how gender affects the adoption of agricultural innovations, highlighting that the adoption choices of men and women may vary based on their responsibilities in farming and decision-making power (Doss and Morris, 2000). Agarwal argues that while both men and women face similar environmental challenges, their strategies for adapting to climate change differ due to socio-cultural factors, resource access, and decision-making power (Agarwal, 2010). The FAO report also highlights how gender roles in agriculture influence the adoption of climate change with specific practices more commonly reported by one gender, such as altering planting schedules (FAO, 2011). Bryan et al. demonstrate in their study of Ethiopian and South African farmers that gender differences play a crucial role in adaptation

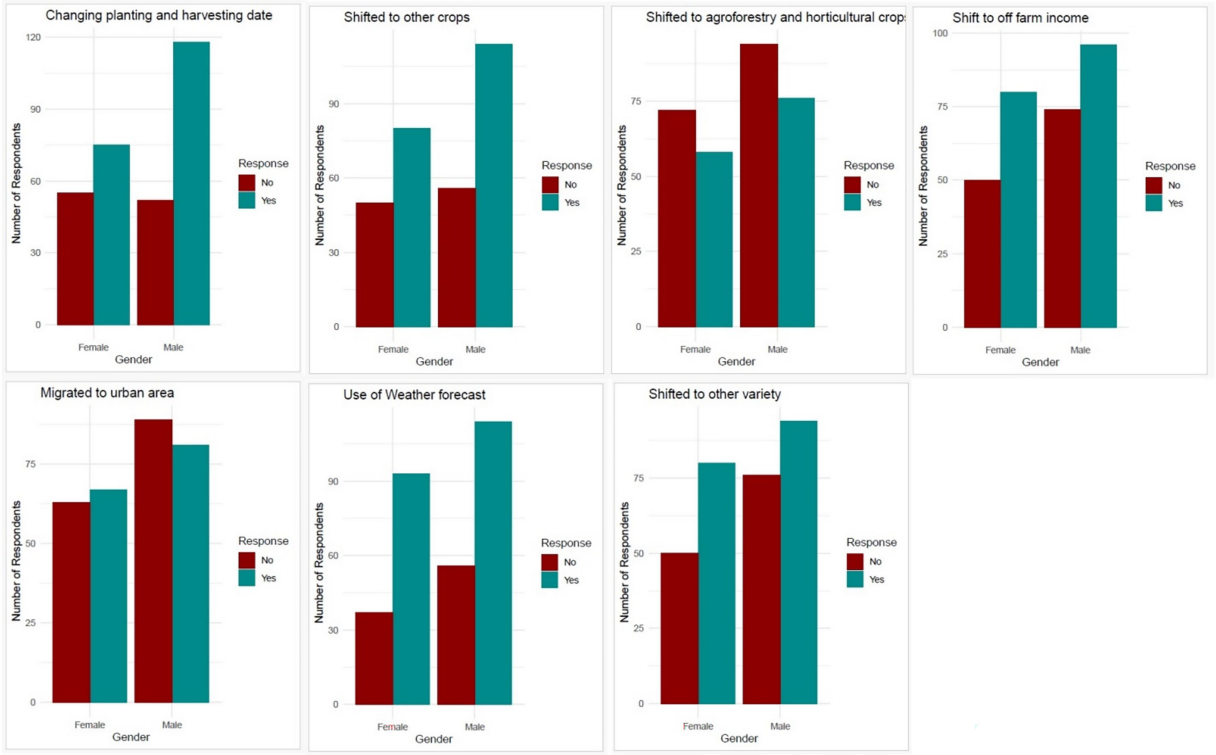


FIGURE 4
Gender-based comparison of adaptive capacity of strategies in response to agricultural changes.

decisions, shaped by access to resources, information, and control over farming activities (Bryan et al., 2009). These studies collectively provide a comprehensive context for understanding the gender-based variations in adaptive capacity, suggesting that while some practices, such as shifting planting and harvesting dates, may show gender differences, other strategies are more universally adopted across genders.

3.5 Factors influencing adaptive capacity of strategies

To explore the relationship between socio-economic characteristics and the adoption of various strategies, we applied a multivariate probit model. The probit model used in this study is suitable for analyzing binary decision outcomes, such as whether or not farmers adopt specific adaptation strategies. Given its flexibility and robustness, the model can be transferred to similar rural contexts in developing countries where smallholder farmers operate under comparable socio-economic and agro-ecological conditions (Aidoo et al., 2021; Mankhin et al., 2024). The model's structure allows for integration of localized variables, making it a useful analytical tool for exploring climate adaptation behavior among diverse farming communities facing climate-induced risks. This model aims to identify how factors such as sex, age, household size, access to credit, access to input subsidy, training received, contact with extension agents, farm size, access to climate information, years of education, and years of farming experience influence farmers' decisions to adopt strategies for coping with climate change. Model fit was assessed using the log-likelihood of the Multinomial Probit Regression model. The log-likelihood value was −1245.649, based on 105 degrees of freedom. Given the similar adoption strategies, the decision was made to combine male and female farmers for analyzing the factors influencing the adaptive capacity. The Probit regression model indicates a positive association between age and the probability of transitioning to off-farm income (0.015) (Table 6). This suggests that older farmers are more inclined to engage in off-farm income-generating activities. With increasing of age, farmers may experience a need for additional financial resources or seek to supplement farm income due to reduced physical capacity for farming or lower agricultural productivity. Moreover, older farmers tend to possess more extensive networks, skills, and life experience, which can facilitate their participation in non-agricultural employment or entrepreneurial ventures. Barrett et al. (2001) also find that in rural Africa, older farmers engage more in non-farm income-generating activities, often due to a decline in physical capacity and the desire for additional financial security.

Access to input subsidies significantly influences farmers' decisions to adapt their agricultural practices, particularly in relation to changing planting and harvesting dates (0.336) and negative effect on adoption of agroforestry and horticultural practices (−0.50). Farmers with access to input subsidies are more likely to adjust their schedules, as the financial support provided subsidies which enables

TABLE 6 Estimating parameters of a multinomial probit regression model to identify factors influencing farmers' adaptive capacity.

Variable	Adaptation strategies						
	Changing planting and harvesting date	Shifted to other crops	Shifted to agroforestry and horticultural crops	Shift to off farm income	Migrated to urban area	Use of Weather forecast	Shifted to other variety
Sex	−0.5415031	−0.0673493	0.093053	0.1234912	0.101595	0.2297441	−0.2181531
Age	−0.3201869	−0.0673493	−0.0057562	0.0151345*	0.0123233	−0.0074983	0.0002629
Household size	−0.0011873	0.0028426	−0.0247481	−0.0138465	0.0123233	−0.0401145	−0.0225677
Access to credit	0.0242314	−0.0838633	0.146709	−0.1670546	0.1572792	0.1021655	−0.1083665
Access to input subsidy	0.3368118*	−0.1278691	−0.5059917**	−0.0175173	−0.1276659	0.0180899	0.016075
Training	0.1363499	−0.2453737	−0.1404106	0.3002538	0.3600111*	0.0534315	0.10853
Contact with extension agents	0.0747852	0.0321234	0.0457678	−0.0462052	0.0717314	−0.0945384	−0.1616592
Farm size hector	−0.0152231	0.3009449	−0.0080561	−0.1080686	−0.5037405	0.1214363	−0.2546553
Access to climate information	0.2501471	0.1080739	−0.0796313	0.0132957	0.3583575*	0.1693507	0.1088093
Years of education	0.0639968*	0.0740778**	0.0682314**	0.0585332**	0.0879987***	0.0350286	0.0051894
Years of farming	0.0420025****	0.0446608****	0.0526515****	−0.0126256	0.0545526****	0.0474866****	0.009861
Constant	−0.5415031	−0.395053	−0.874348	−0.6082407	−2.2397511****	−0.4133739	0.4396178

Multinomial probit regression model; Wald test, log-likelihood: −1245.649 on 105 Df; *$p < 0.10$, **$p < 0.05$, ***$p < 0.01$, ****$p < 0.001$.

them to invest in essential inputs such as seeds and fertilizers. This financial assistance allows farmers to better respond to seasonal variability and climate fluctuations by ensuring timely and effective adjustments in planting and harvesting and encourage the continuation of farming activities rather than diversifying into alternative agricultural practices. Input subsidies for seeds and fertilizers supported the adoption of improved agricultural practices, including changes in planting schedules to cope with climate variability in Ethiopia (Belay et al., 2022).

Training and access to climate information both play a significant role in influencing farmers' adaptive capacity, particularly in relation to migration (0.36) indicating that farmers who receive training and have access to climate information are more likely to migrate in urban areas. Training equips farmers with the tools necessary to adapt to environmental and economic challenges, making migration an attractive and viable option. Agricultural training exposes farmers to modern techniques and climate-smart practices, which may not be fully applicable in rural settings. In essence, training not only enhances farmers' skill sets but also encourages them to seek migration to cities, where they can apply their knowledge in more diverse and lucrative ways. Consequently, farmers with access to reliable climate data may be drawn to urban areas where better infrastructure, higher income opportunities, and alternative agricultural-related jobs are available. By gaining a better understanding of climate patterns, farmers may recognize the limitations of rural farming and the potential for improved economic stability in urban areas. Research by Gray and Mueller (2012) suggests that farmers who have access to climate data are more likely to migrate, as it helps them assess agricultural risks, such as droughts or extreme weather, and realize the limited economic opportunities in rural areas. Similarly, it was suggested that when farmers are trained in new agricultural techniques or exposed to alternative livelihood strategies, they are more likely to migrate (Migration, Agriculture and Rural Development, 2025; FAO, 2018).

In addition, Education plays a crucial role in shaping farmers' responses to changing agricultural conditions, as demonstrated by the Probit regression model, which reveals that years of education positively influence adaptive capacity of all five strategies. Educated farmers are more likely to adjust their planting and harvesting dates (0.063) as they have a better understanding of climate patterns and seasonal variations (Table 6). Educated farmers possess the knowledge and skills necessary to interpret climate information and apply it to their agricultural decisions (Deressa et al., 2009). In addition, they shifted to other crops and agroforestry and horticultural practices (0.07), as educated farmers are more likely to switch to alternative crops as a risk management strategy and are more aware of sustainable land management techniques (FAO Knowledge Repository, 2015). Educated farmers also migrated to urban areas (0.08), and engage in off-farm income activities (0.06), as education provides the skills and qualifications for non-farm job opportunities in urban areas. Education shapes migration patterns by enhancing individuals' ability to take advantage of better-paying non-farm economic opportunities such as salaried jobs, small businesses, or trade in cities (Aydemir et al., 2022; Boccanfuso et al., 2015; Sen et al., 2021). Overall, education empowers farmers to make informed decisions, adopt innovative practices, diversify their income sources, and better adapt to environmental and economic challenges, highlighting its critical role in enhancing resilience to climate change and promoting sustainable farming practices.

The Probit regression model reveals significant relationships between years of farming experience and various strategy's adaptive capacity employed by farmers. Firstly, years of farming experience positively influence farmers' decisions to change their planting and harvesting dates and they shifted to other crops (0.04) as well as agroforestry and horticultural practices (0.05) (Table 6). Experienced farmers are more adept at recognizing climate variations and adjusting their schedules accordingly, ensuring better adaptation to seasonal changes. They are more likely to adjust planting and harvesting schedules to ensure better synchronization with seasonal changes, as they are familiar with local climate patterns and more proactive in adopting strategies and select more resilient and diversification crops with changing weather conditions (Fosu-Mensah et al., 2012; Cano and Castro Campos, 2024; Yeleliere et al., 2023; Berhanu et al., 2024). Experienced farmers, through their knowledge of ecosystem dynamics, are better equipped to integrate trees into their farming systems and adopt horticultural practices that enhance resilience to climate change (Jovanelly et al., 2025). Lastly, we found years of farming experience significantly influence both the migration to urban areas and the use of weather forecasts with coefficient of (0.05). Their accumulated knowledge of farming also by utilizing weather forecasts allowing them to seek alternative opportunities in cities where they can secure stable income sources for improving their quality of (Bangladesh Bureau of Statistics (BBS), 2024; Wang and Cai, 2009).

3.6 Predicted probabilities for adaptive capacity of strategies

The predicted probabilities for adaption capacity of each strategy in this dataset highlight varying degrees of response to environmental, economic, and socio-demographic factors. The higher probabilities (Figure 5) for changing planting and harvesting dates (63.76%), shifting to other crops (64.50%), and using weather forecasts (68.85%) suggest that these are the most commonly adopted strategies, likely driven by immediate needs for climate adaptation and resource optimization in agriculture. These behaviors indicate a high level of awareness and responsiveness to climatic variability, with farmers increasingly using weather information to inform their decisions, adjusting planting schedules and crop choices to optimize yields. On the other hand, strategies such as shifting to agroforestry and horticultural crops (44.41%) and migrating to urban areas (48.88%) show less widespread adoption but remain significant. These behaviors reflect a growing trend towards diversification in land use and livelihoods, influenced by factors like changing land availability, government incentives for agroforestry, or the economic pull of urban centers. The shift to off-farm income (58.53%) further illustrates a crucial adaptation strategy, particularly in rural areas, where individuals are increasingly seeking financial stability outside agriculture due to economic challenges or limited access to resources. The relatively balanced probability for shifting to other crop varieties (51.34%) highlights a middle-ground adaptation strategy, where a large portion of individuals are experimenting with new varieties to

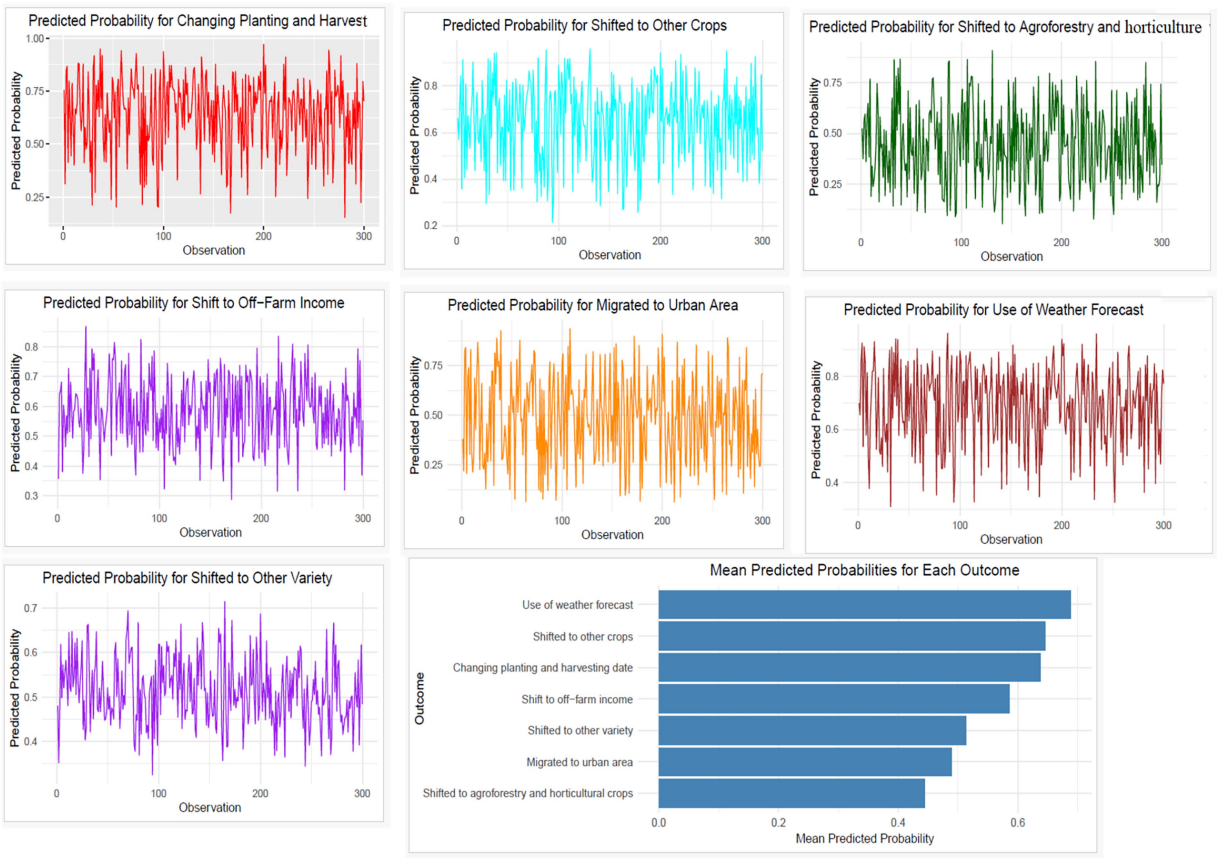


FIGURE 5
Predicted probabilities of different strategy's adaption capacity and mean predicted probabilities of different strategies.

respond to evolving climate conditions or market demand. Recent studies highlight the diverse adaptive capacity employed by smallholder farmers in response to climate change, for instance altering planting dates and crop varieties (Tessema et al., 2019), switching to off-farm income (Fonjong et al., 2024) and migration (Quarshie et al., 2023) particularly in regions vulnerable to environmental stressors. These findings emphasize that adaptation to climate change and other external pressures is multifaceted, with individuals employing a mix of short-term and long-term strategies depending on their immediate circumstances, economic motivations, and available resources. This variability underscores the need for targeted interventions that address the diverse challenges faced by different segments of the population.

3.7 The relationship between education, experience and adaption strategies

Since education and experience are key to adaptation, the correlation between these factors and the likelihood of adopting strategies is significant, suggesting that more education and experience improve farmers' ability to adapt to climate change. The correlation between the predicted probability of various stratagy's adaption capacity and education reveals important insights into how education influences farmers' decisions (Figure 6A). For example, higher levels of education are positively correlated with an increased likelihood of farmers adopting strategies such as changing planting and harvesting dates, shifting to other crops, engaging in agroforestry, seeking off-farm income, or migrating to urban areas. The correlation coefficient indicates a moderate positive relationship ($R > 0.50$, $p < 0.0001$) between education and the predicted probabilities of these strategies (Figure 6A). Education has been shown to play a crucial role in enhancing farmers' adaptive capacity to climate change. Studies have demonstrated that higher education levels are positively correlated with the adoption of a variety of strategies. For instance, farmers with higher education levels were more likely to adopt innovative agricultural practices such as changing planting schedules, experimenting with new crop varieties (Hu et al., 2024) and engage in practices like agroforestry. This suggests that education equips farmers with the knowledge and decision-making skills necessary to respond to climate change challenges and economic pressures, thus enhancing their adaptive capacity.

The positive correlation (Figure 6B) between farming experience and the predicted probabilities of changing planting and harvesting dates, shifting to other crops, shifting to agroforestry and horticultural crops, migrating to urban areas, and using weather forecasts suggests that as farmers gain more experience, they are more likely to adopt these adaptive strategies. The correlation coefficient between 0.70 and

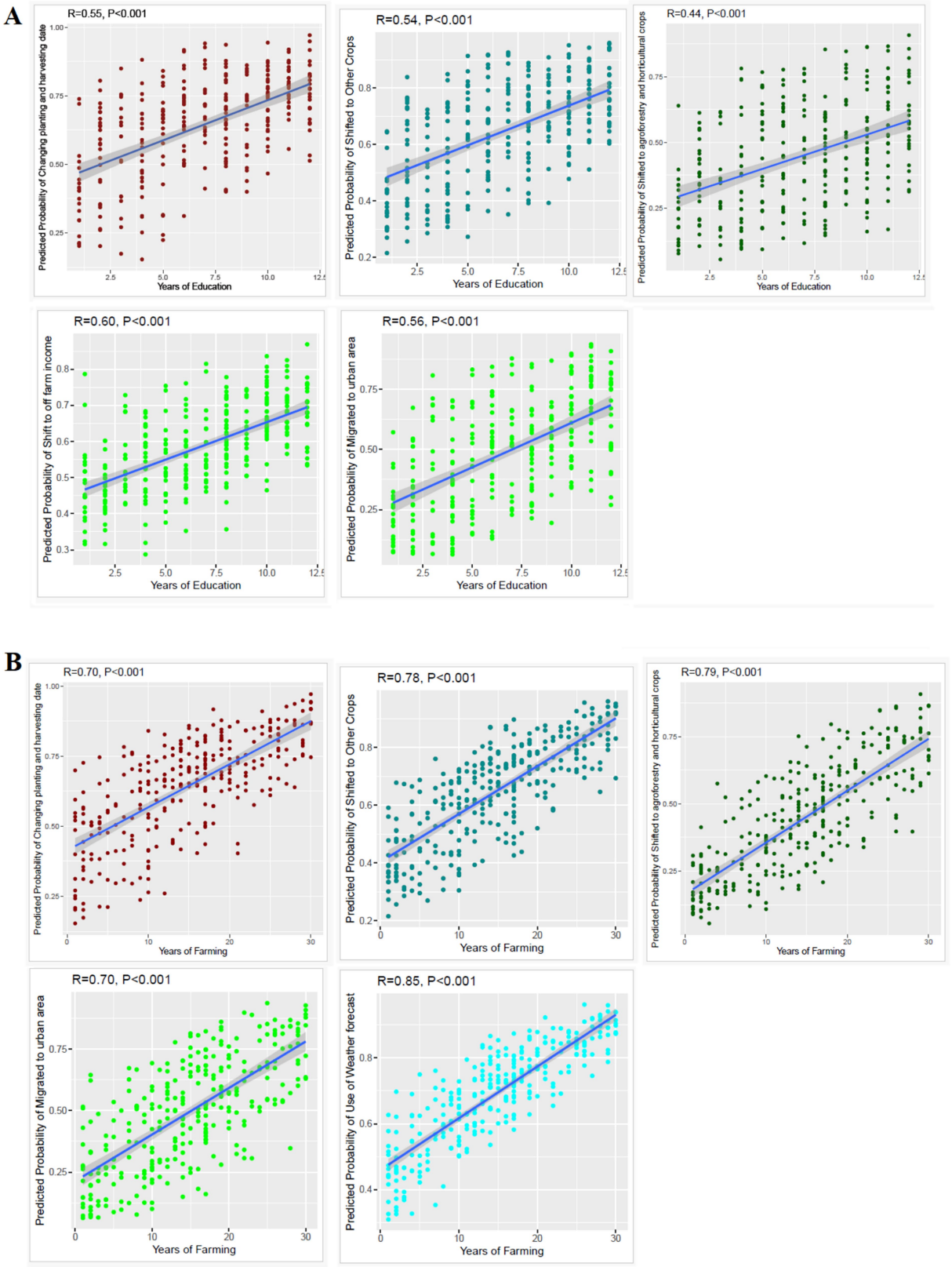


FIGURE 6
Correlation of predicted probability with education **(A)** and farming experience **(B)**.

0.85 indicates a strong to very strong positive relationship (Figure 6B), meaning that the more years of farming experience a farmer has, the more likely they are to engage in behaviors that reflect adaptation to climate variability or changing agricultural conditions. Studies have consistently shown that farming experience enhances the ability to make informed decisions regarding the timing of planting, crop diversification (Yahaya et al., 2023) and adopting of agroforestry. Furthermore, Adger et al. (2005) emphasized that farmers with longer agricultural careers often possess greater adaptive capacity because they can more easily incorporate climate information into their decision-making processes. In summary, farming experience appears to play a crucial role in shaping adaptive behaviors, with more experienced farmers demonstrating a higher likelihood of adopting strategies that reflect both practical knowledge and the need for resilience in the face of changing conditions.

The correlation analysis reveals strong positive associations between farming experience, education, and the predicted probabilities of adopting strategies. These results align closely with the Probit regression model, which identifies both variables as significant predictors of adaptive behavior. The consistency between the correlation findings and model outputs affirms the model's validity and suggests it effectively captures real-world decision-making patterns. Specifically, the results indicate that more experienced and better-educated farmers are significantly more likely to adopt strategies. This reinforces the critical influence of farming experience and education on adaptive capacity. The strong correlations further confirm that the model's predicted probabilities reflect actual trends in the data, enhancing confidence in its predictive reliability and utility for forecasting agricultural adaptation behavior.

4 Concluding remarks

This study underscores the distinct climate related challenges confronting smallholder nut farmers on Hatiya Island, Bangladesh, where rising sea levels, salinity intrusion, and erratic weather patterns continue to undermine agricultural productivity. While both male and female farmers share comparable perceptions of climate risks, notable gender differences emerge in the attribution of causes and the adaptive capacity of strategies. Key factors education, farming experience, and access to subsidies play a significant role in enabling farmers to adopt measures like adjusting planting schedules, diversifying crops, and utilizing weather forecasts.

To enhance resilience, policy interventions must prioritize gender-sensitive approaches, expand access to climate information, and promote sustainable subsidy mechanisms. Investments in education, digital tools, and rural infrastructure are also essential. Additionally, supporting off-farm income and addressing rural-to-urban migration can contribute to long-term livelihood stability.

Despite observed progress, barriers such as limited resource access and inadequate extension services remain. These findings point to the need for targeted, evidence-based interventions and further research to evaluate the long-term effectiveness of adaptation strategies. Strengthening the adaptive capacity of island-based nut farmers through inclusive, collaborative, and sustainable approaches is critical to ensuring agricultural sustainability and protecting rural livelihoods in the face of escalating climate threats.

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

RB: Funding acquisition, Software, Formal analysis, Conceptualization, Writing – review & editing, Supervision, Methodology, Writing – original draft, Investigation, Visualization, Data curation. AA: Writing – review & editing, Supervision, Formal analysis, Project administration, Writing – original draft, Methodology, Resources, Investigation, Data curation, Visualization, Validation. DE: Data curation, Methodology, Supervision, Writing – original draft, Writing – review & editing.

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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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The Greater Bay Area as a hotspot: interacting impacts of urbanization and extreme events on wet-bulb temperatures in Guangdong Province

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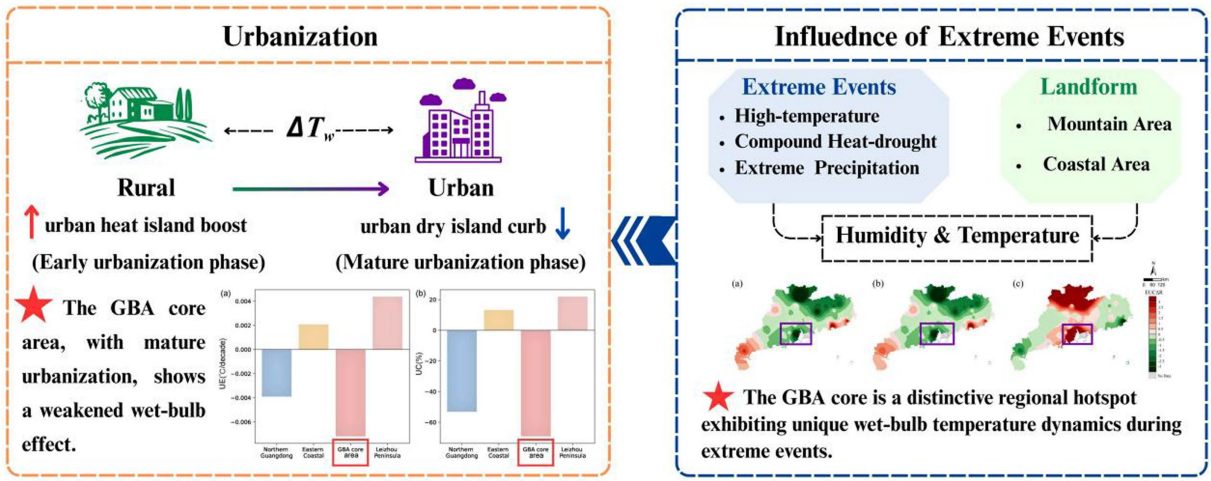
Amidst rapid urbanization and an increasing frequency of extreme events, urban climate stress is intensifying and potentially affecting wet-bulb temperature (WBT), a key indicator of human-perceived thermal stress. This study examined the combined effects of urbanization and extreme events on the WBT dynamics in Guangdong Province, a humid tropical region in China. Using long-term meteorological data spanning five decades and urbanization metrics, we systematically analyzed urban–rural WBT differences using paired station comparisons and quantified the contribution of urbanization. Key findings highlight urban–rural WBT differences across three distinct urbanization stages: (a) Initial urbanization, where heat island effects dominate and amplify WBT differences; (b) Rapid urbanization, characterized by impervious surface expansion that widens WBT disparities to their peak, with the urban–rural difference increasing by 0.0027° C decade^{-1} ($p < 0.001$); and (c) Mature urbanization (e.g., Guangdong-Hong Kong-Macao Greater Bay Area, GBA), where dry island effects reduce humidity, thereby narrowing urban–rural gaps. Furthermore, extreme weather events alter these urban–rural WBT patterns. High-temperature and compound heat-drought events can reduce WBT differences, in some cases by a factor of three, while periods of extreme precipitation can amplify them. These findings underscore the critical impacts of urbanization and extreme events on urban thermal stress. This understanding is crucial for evaluating human heat stress and informing urban risk planning, particularly in the context of advancing urbanization and climate change in urban agglomerations.

KEYWORDS

extreme events, urbanization, urban–rural wet-bulb temperature differences, urban agglomeration, climate warming

Highlights

- Wet-bulb temperature difference (WBT) between urban and rural areas in humid Guangdong was investigated.
- Extreme events (high temperature, compound heat-drought, and extreme precipitation) impact urban–rural WBT differences.
- The Greater Bay Area is a hotspot showing unique WBT patterns.
- Both urbanization and extreme events affect urban–rural wet-bulb temperature differences.



GRAPHICAL ABSTRACT

1 Introduction

In a warming climate, the increasing frequency of extreme events (e.g., high temperature, compound heat-drought, and extreme precipitation) presents a significant threat. These events not only trigger ecological crises such as ecosystem degradation and loss of habitat (Qu et al., 2023; Walsh et al., 2020) but also have far-reaching impacts on agricultural production (Han et al., 2024), socio-economic development (Newman and Noy, 2023), and human health (Clayton, 2020; Ebi et al., 2021). An event is typically classified as "extreme" when a meteorological variable exceeds an established threshold, corresponding to a low probability of occurrence, typically below 10% (Qin et al., 2015). It is crucial to investigate the multidimensional effects of extreme events (Wang et al., 2022). Urbanization, marked by rising population density and expansion of impervious surfaces, restructures social-economic dynamics while heightening climate risks in densely populated urban areas (Jones, 2005; Ali et al., 2013; Fu and Weng, 2016; Hanson et al., 2011). Furthermore, increased atmospheric pollutants and population density during urban development significantly influence extreme events (Jiao et al., 2020).

As a key indicator of human-perceived thermal stress (Zhang et al., 2023), wet-bulb temperature (WBT) has recently emerged as an important indicator for investigating how urban meteorological environments evolve and how extreme weather events alter climatic conditions, which are often used for urban planning and safeguarding public health (Justine et al., 2023; Zhang et al., 2023; Rahman et al., 2022). Urban Heat Island (UHI) processes, driven by impervious surface expansion, raise urban air temperatures and consequently WBT (Cho, 2022; Wong et al., 2021). Previous studies have investigated the combined roles of temperature and moisture dynamics, highlighting how interactions among urban morphology, building configurations, and climatic conditions drive WBT increases through both warming and humidity changes (Lu et al., 2021; Wang et al., 2019). Regarding extreme events, heatwaves can raise WBT by 2–6° C in humid environments (Shreevastava et al., 2023), and droughts amplify WBT by suppressing evaporative cooling (Zhou et al., 2022). The effect of extreme precipitation is more complex: while rainfall can cause evaporative cooling that reduces WBT (Yin et al., 2023), the accumulation of atmospheric humidity before a storm can also cause transient increases (Ivanovich et al., 2022; Wu, 2000).

Although progress has been made in understanding urbanization's impact on WBT and its responses to extreme events, several gaps remain. First, although previous studies have documented urban–rural differences in WBT, its magnitude and mechanisms in humid regions remain uncertain (Zhang et al., 2023). Second, while the individual roles of urbanization and extreme events have been explored (Chen H. P. et al., 2024; Chen Y. et al., 2024; Luo and Lau, 2021; Yao et al., 2022), few have examined their combined effects on wet-bulb temperature. Finally, most studies are limited by short time frames or coarse spatial scales (Lu et al., 2021; Zhang et al., 2023), particularly lacking detailed, long-term analysis for humid regions. Addressing these gaps is an urgent research challenge, particularly for urban agglomerations where dense populations face heightened heat stress.

To address these gaps, this study focuses on Guangdong Province in China (encompassing Guangdong-Hong Kong-Macao Greater Bay Area, GBA) as a case study of a humid and highly urbanized region. First, we use long-term meteorological and urban development data to quantify the urban–rural WBT difference, evaluating the effect of urbanization. Second, we quantitatively assess how extreme events, namely heatwaves, compound heat-drought events, and extreme precipitation, alter this effect. Finally, we investigate the combined effect of urbanization and extreme weather on the urban–rural WBT differences, providing insights for developing climate-adaptive strategies in humid urban agglomerations.

2 Materials and methods

This study investigates the effects of urbanization and extreme events on urban–rural wet-bulb temperature differences in Guangdong Province. First, we classified 86 meteorological stations as either urban or rural based on population size, population density, and land cover, and established urban–rural station pairs considering elevation and spatial distance. Second, we identified three types of extreme weather events:

high-temperature events, extreme precipitation, and compound heat-drought events. Finally, we assessed the response of WBT differences to extreme events using the Extreme Urban-Countryside Change Ratio ($EUC\Delta R$).

2.1 Study area

Located within the tropical and subtropical monsoon zone of southern China (Figure 1), Guangdong Province experiences high temperatures and humidity year-round, with hot, humid summers and warm, humid winters, which is a typical humid tropical region (Ye et al., 2022; Zhang et al., 2017). It is one of China's most rapidly urbanizing provinces (Cai and Deng, 2020), with the Pearl River Delta-centered Guangdong-Hong Kong-Macao Greater Bay Area (GBA) being one of the world's largest bay economies (Hui et al., 2020). Guangdong experienced more frequent and intense heatwaves and extreme rainfall in recent years due to urbanization and global climate change. For example, the frequency of severe heatwaves rose by 0.141 events per year between 1960 and 2015 (Jiang et al., 2015; Wu and Du, 2011; Zhang et al., 2018). Therefore, Guangdong Province encompassing GBA is a particularly suitable region for investigating the impacts of urbanization and extreme weather on wet-bulb temperature in humid regions.

Long-term meteorological observations, including daily precipitation, air temperature, and relative humidity, were collected from 86 stations in Guangdong (Figure 2; Hong Kong and Macao excluded due to inaccessible data) via the China Meteorological Data Network (CMDN) for 1951–2018. Land use data were obtained from the China Land Cover Dataset (CLCD) on Google Earth Engine, covering 1985–2019. Population size data were obtained from the 2010 Sixth National Census, while population density data were sourced from the Gridded Population of the World Version 4 (GPWv4).

2.2 Criteria for urban–rural station pairing

To investigate the impact of urbanization on WBT, we first classified 86 meteorological stations in Guangdong Province as either urban or rural. This classification was based on a scoring system using three indicators: population size, population density, and land cover (Zhong et al., 2024).

(a) Population size was retrieved from the 2010 Sixth National Census at the county level. Stations in counties with populations <500,000 were scored as rural (score = 0), those with populations >1,000,000 as urban (score = 1), and those

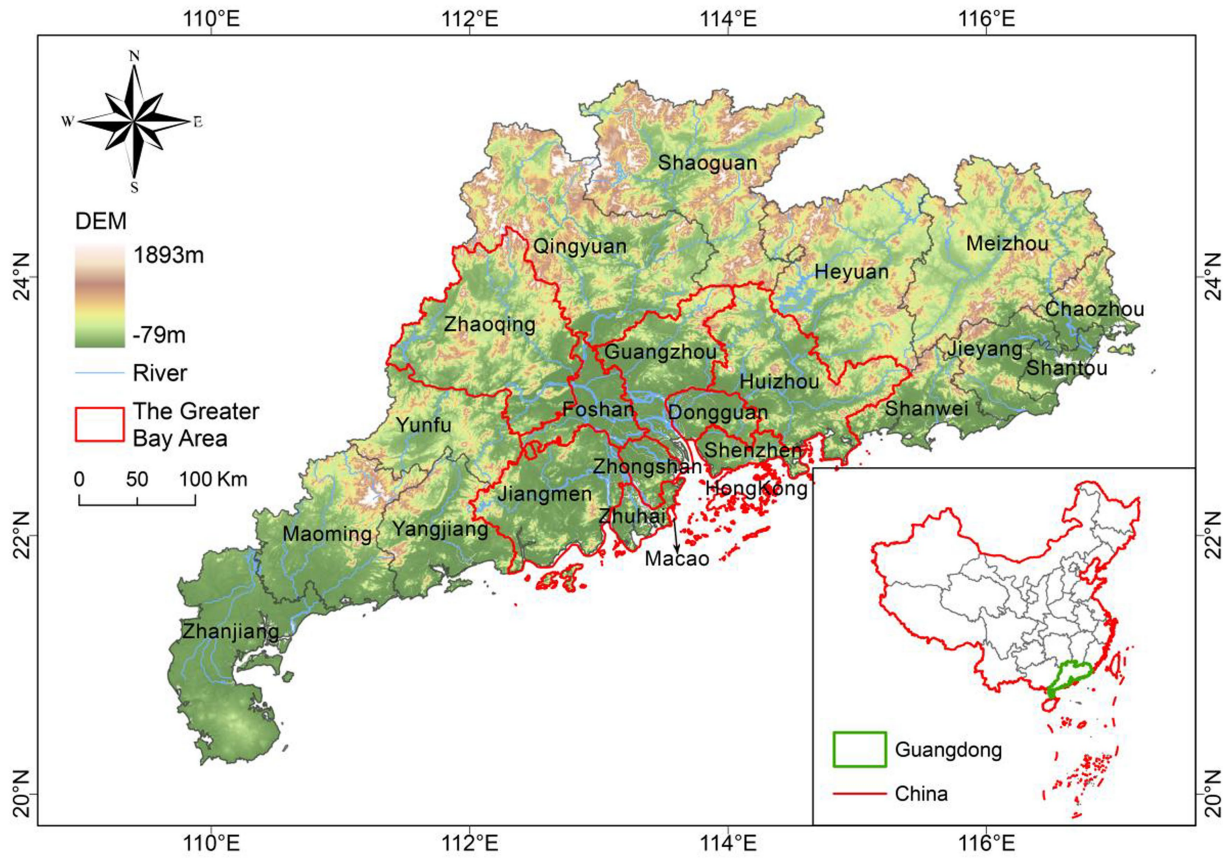


FIGURE 1
Topographic map of the study area, Guangdong Province. The map displays the elevation based on a Digital Elevation Model (DEM), major rivers, and cities. The boundary of the Guangdong-Hong Kong-Macao Greater Bay Area (GBA) is outlined. The inset shows the location of Guangdong Province within China.

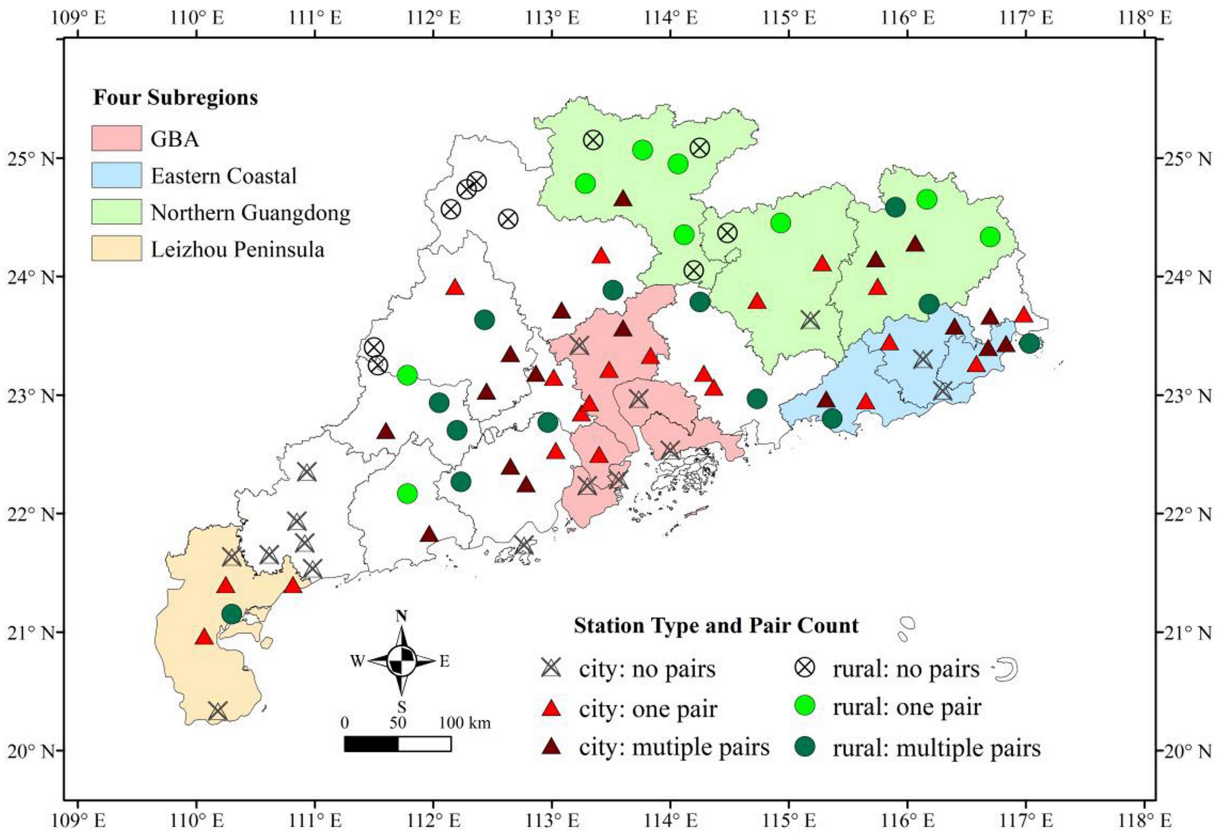


FIGURE 2
Spatial distribution of meteorological stations across Guangdong Province, classified as urban or rural. The symbols indicate both the station type and the outcome of the pairing process (e.g., paired, unpaired, or multiple pairs), as detailed in the legend. The map also delineates the four subregions used for regional analysis: the Greater Bay Area (GBA), Eastern Coastal, Northern Guangdong, and Leizhou Peninsula.

with populations between 500,000 and 1,000,000 received a score of 0.5.

(b) Population density data were sourced from the Gridded Population of the World, version 4 (GPWv4). For each station, we assigned the maximum population density value from its surrounding nine grid cells. Stations with a density less than 70% of the average density across all stations were scored as rural (score = 0), those with a density greater than 99% of the average were scored as urban (score = 1), and those in between received a score of 0.5.

(c) Land cover data were sourced from the China Land Cover Dataset (CLCD). For each station, we calculated the proportion of impervious surface within a 3-pixel radius buffer. Stations were classified as rural if impervious surface coverage was less than 20% (score = 0), urban if it exceeded 40% (score = 1), and received a score of 0.5 for values between 20 and 40%.

After aggregating the three scores for each station, stations with a cumulative score of ≥2 were designated as urban, while those scoring below this threshold were categorized as rural (Zhong et al., 2024). Urban–rural station pairs were selected based on strict criteria for spatial and climatic comparability. The pairing process adhered to the following conditions: (1) an elevation difference of less than 100 m, (2) a spatial distance of less than 80 km, and (3) a latitudinal distance of less than 50 km. To account for elevation-related temperature differences, a vertical lapse rate of 0.0065° C m^{-1} was applied (Zhang et al., 2023). For each urban station, if only one rural station met the criteria, it was selected as the pair. In cases where multiple rural stations qualified, the geographically nearest station was chosen (Jiang et al., 2020).

2.3 Urban–rural WBT differences

The wet-bulb temperature (*WBT*, ° C) was calculated using elevation-corrected air temperatures and relative humidity (Equation 1, Stull, 2011):

$$\begin{aligned} WBT = {} & T \cdot \operatorname{atan}\left[0.151977 \cdot \left(RH + 8.33659\right)^{1/2}\right] \\ & + \operatorname{atan}\left(T + RH\right) - \operatorname{atan}\left(RH - 1.676331\right) \\ & + 0.00391838 \cdot \left(RH\right)^{3/2} \cdot \operatorname{atan}\left(0.023101 \cdot RH\right) - 4.68035 \end{aligned} \quad (1)$$

where T is air temperature (° C) and RH is relative humidity (%). The inverse tangent function (*atan*) is used as a nonlinear correction term, enabling a more accurate representation of WBT variations under diverse meteorological conditions.

The urban–rural WBT difference (ΔWBT, °C) was then calculated for each station pair over the period 1967–2018. Although

meteorological records at some observation sites extend back to 1951, the 1967–2018 period was selected to ensure data from a more consistent and comprehensive network of stations, thereby maintaining temporal consistency and data reliability. The ΔWBT for each station pair was then computed in Equation 2:

$$\Delta WBT = WBT_u - WBT_r \tag{2}$$

where WBT_u refers to the WBT at the urban station, and WBT_r refers to the WBT at the rural station.

2.4 Extreme events and urbanization

2.4.1 Identification of extreme events

We focused on three types of extreme events, namely high temperature, extreme precipitation, and compound heat-drought events, which were identified to assess the changes in WBT during these periods relative to normal non-event conditions. The specific criteria for these events are presented in Table 1.

2.4.2 The effect of extreme events

The impact of extreme events on the urban–rural WBT differences is quantified using the change in the difference during extreme events relative to non-event periods. We define a metric, the Extreme Urban-Countryside Change Ratio ($EUC\Delta R$), as shown in Equation 3. Its purpose is to provide a measure of how much the urban–rural WBT difference shifts during an extreme event. This allows us to compare the response across different locations and identify regional hotspots.

$$EUC\Delta R = \frac{\Delta WBT_{ext} - \Delta WBT_{non-ext}}{\left|\Delta WBT_{non-ext}\right|} \tag{3}$$

where ΔWBT_{ext} represents the urban–rural WBT difference during extreme events, and $\Delta WBT_{non-ext}$ represents the difference during non-extreme events. The median and mean values of $EUC\Delta R$ were interpolated using inverse distance weighting (IDW) to explore their spatial variation patterns. A positive $EUC\Delta R$ value denotes that the urban–rural WBT difference is greater during extreme events than during non-event periods. Conversely, a negative value indicates the difference is reduced. An $EUC\Delta R$ of zero implies the extreme event had a limited effect on the urban–rural WBT difference relative to the non-event baseline.

TABLE 1 Criteria for identifying extreme events.

Types of extreme events	Criteria
High-temperature event	Daily maximum temperature ≥35° C (Ding et al., 2022)
Extreme-precipitation event	Precipitation greater than the 95th percentile (Khan et al., 2023)
Compound heat-drought event	SPI ≤ −0.5 and daily maximum temperature ≥ 35° C (Jiang et al., 2023)

2.4.3 The effect of urbanization

To quantify the impact of urbanization on WBT trends, we used the Urbanization Effect (UE) indicator, defined as the difference between the WBT trends of urban and rural stations, as shown in Equation 4 (Zhong et al., 2024):

$$UE = Trend_u - Trend_r \tag{4}$$

where $Trend_u$ is the WBT trend for urban stations and $Trend_r$ is the WBT trend for rural stations. A positive UE value signifies that urban areas are experiencing a faster warming trend in WBT compared to surrounding rural areas, suggesting an exacerbating effect of urbanization. Conversely, a negative value indicates that urban WBT is warming more slowly than in rural areas, potentially implying that urbanization has a mitigating effect on WBT rise or that other local factors are dominant.

To quantify the extent to which urbanization affects WBT, we used the Urbanization Contribution (UC) indicator (Equation 5, Zhong et al., 2024):

$$UC = \frac{UE}{Trend_u} \times 100\% \tag{5}$$

The UC indicator represents the percentage of the observed urban WBT trend that can be attributed to local urbanization. For instance, a UC value of 30% suggests that 30% of the total WBT trend in the urban station is due to this urbanization effect. A negative UC value would typically occur if the urbanization effect and the urban trend have opposite signs.

All WBT trends were calculated using the Block Bootstrap method, a non-parametric resampling technique designed for autocorrelated time series data (Härdle et al., 2003). The main steps are described below.

For time series data $\{X_1, X_2, \cdots, X_n\}$, pseudo-samples are generated by dividing the data into fixed-length blocks b and randomly sampling these blocks with replacement. The data is first divided into n-b + 1 overlapping sliding blocks (B) of length b Equation 6:

$$\begin{aligned} B_1 &= \{X_1, X_2, \cdots, X_b\} \\ B_2 &= \{X_2, X_3, \cdots, X_{b+1}\} \\ &\vdots \\ B_{n-b+1} &= \{X_{n-b+1}, \cdots, X_n\} \end{aligned} \tag{6}$$

Next, $k = \left[\frac{n}{b}\right]$ blocks are randomly selected from the sliding block with replacement and combined to form the pseudo-sample $\{X_1^*, X_2^*, \cdots, X_n^*\}$.

A linear regression of year (independent variable X) and temperature (dependent variable Y) in the pseudo-sample is modeled with Equation 7:

$$Y = \beta_0 + \beta_1 X + \varepsilon \tag{7}$$

where Y is the temperature, X is the year, β_0 is the intercept, β_1 is the slope, and ε is the error term. These steps are repeated for each generated pseudo-sample. The resulting slope β_1 are recorded to form a slope distribution $\{\beta_1^*\}$, and its mean and 95% confidence interval are calculated by Equation 8:

$$CI_{95\%} = \left[\beta_1^{*(2.5\%)}, \beta_1^{*(97.5\%)} \right] \quad (8)$$

Note that interaction between urbanization and extreme climate events is complex and nonlinear (Zhao et al., 2021; Chen H. P. et al., 2024; Chen Y. et al., 2024). Rather than deconstructing the underlying nonlinear physics, the UE, UC, and $EUC\Delta R$ were therefore used as diagnostic indices to quantify and characterize the net outcome of these complex interactions across different regions and event types.

3 Results

3.1 Distribution of paired stations

Figure 2 illustrates the spatial distribution of final urban–rural meteorological station pairs. Initial attempts at pairing revealed challenges, namely: the issue of one-to-many associations (i.e., a single site having multiple potential matches) and the failure to find pairs for all sites, a problem most common in regions with dense station distributions. To address these challenges, a refined two-step pairing strategy was adopted. First, all urban stations for which at least one potential rural counterpart could be identified were retained. Second, for each of these urban stations, the geographically closest rural station was selected as its definitive pair. This process resulted in 38 distinct urban–rural station pairs, providing coverage for the majority (90.9%) of cities in Guangdong Province. The four subregions (the Greater Bay Area, Eastern Coastal, Northern Guangdong, and Leizhou Peninsula) were used in subsequent analysis and highlighted to emphasize their spatial distribution (Figure 2).

3.2 Impact of urbanization on urban–rural WBT differences

Figure 3 presents the temporal variations of annual mean WBT for all stations and for the urban and rural subgroups. During the study period, the overall mean WBT across all stations was 19.39° C. Urban stations exhibited a higher average WBT of 19.48° C, compared to 19.04° C for rural stations. This observed difference (0.44° C) implies an urban impact on moist heat conditions. Overall, the mean WBT increased slightly at a rate of 0.136° C decade^{-1} (p value = 0.001). The rate of increase was 0.132° C decade^{-1} (p value = 0.001) for urban stations, compared to a slightly higher rate of 0.151° C decade^{-1} (p value <0.001) for rural stations. This difference in warming rates resulted in a slight narrowing of the urban–rural WBT difference over the study period.

To assess the spatial distribution of urbanization's impact on annual mean WBT changes, the UE and UC metrics were calculated for each station pair (Figure 4). On average, urban WBT increased 0.0027° C decade^{-1} ($p < 0.001$) faster than rural WBT. This positive UE demonstrates that urbanization has exacerbated the urban–rural WBT difference. Furthermore, the UC analysis revealed that within Guangdong Province, urbanization accounted for an average of 3.13% of the total observed WBT increase in urban areas, highlighting its contribution to the warming of these urban environments.

Spatially, stations exhibiting statistically significant upward WBT trends were widespread, particularly in the GBA and in western and eastern Guangdong. Within the GBA, urban stations exhibiting UE values less than 0 are predominantly found in the Pearl River Delta (PRD), particularly in cities like Guangzhou, Foshan, and Jiangmen. This suggests that in these mature, highly urbanized centers, the net impact of ongoing urban development on WBT trends is less

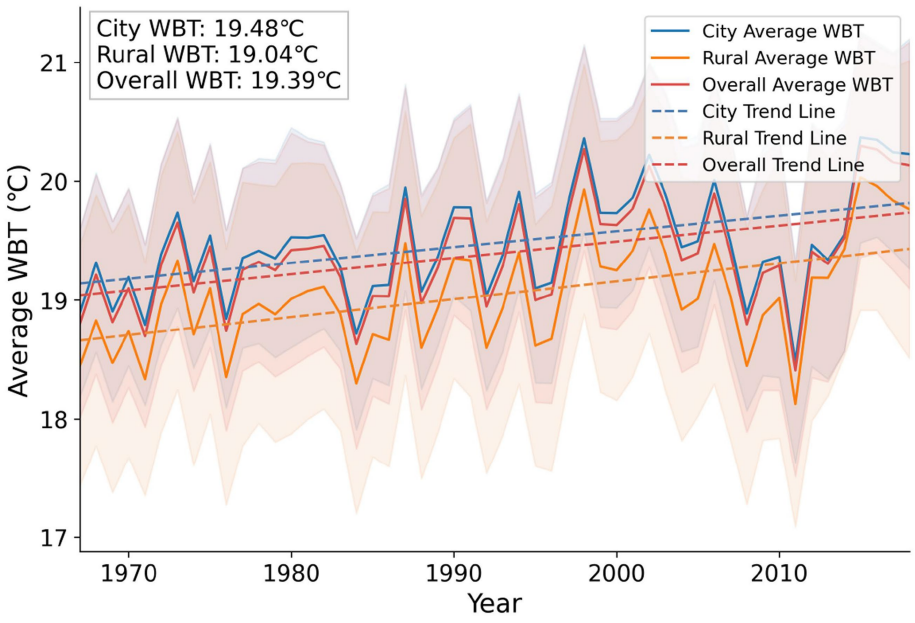


FIGURE 3
Time series of annual mean WBT across Guangdong province from 1967 to 2018. Solid lines represent the annual mean WBT for urban, rural, and all station groups, with the corresponding shaded bands indicating ± one standard deviation. Dashed lines show the linear trend for each group. The inset text provides the long-term mean WBT for each group over the entire study period.

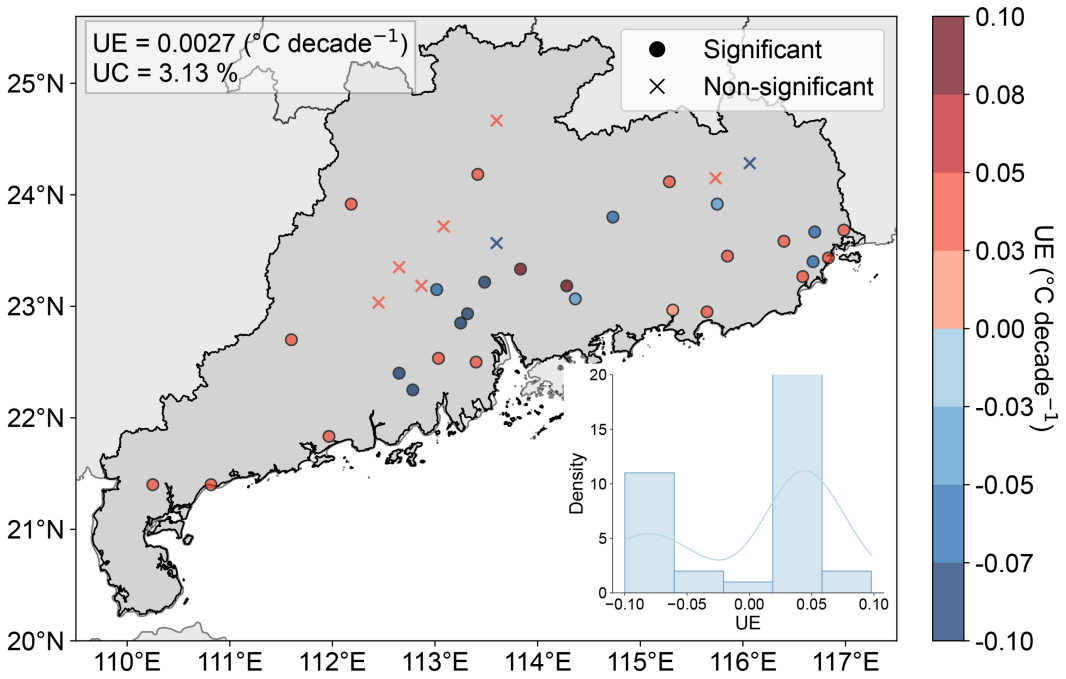


FIGURE 4
Spatial distribution of the urbanization effect (UE) on annual mean WBT trends across Guangdong Province. The color of each point indicates the magnitude of the UE, while symbols distinguish between statistically significant (circles, $p < 0.05$) and non-significant (crosses) trends. The inset displays the probability density function of all UE values, and the text overlay provides the province-wide mean UE and urbanization contribution (UC).

pronounced compared to their rural counterparts, potentially leading to a stabilization or even a narrowing of the urban–rural WBT difference (Liang et al., 2022). Conversely, stations in regions such as eastern Guangdong, characterized by rapid recent expansion, showed higher rates of WBT warming and larger urbanization contributions (Zhong et al., 2024).

3.3 Spatial patterns of urban–rural WBT differences under extreme events

To better understand urban–rural WBT differences across Guangdong, we analyzed WBT trends in four primary subregions, namely the northern Guangdong, the GBA, the eastern coast, and the Leizhou Peninsula (delineated in Figure 2; trends are presented in Figure 5). Distinct regional patterns emerged. In the rapidly urbanizing Leizhou Peninsula, urban areas exhibited a faster rise in WBT (0.175° C decade^{-1}, $p < 0.001$) than rural areas (0.145° C decade^{-1}, $p = 0.004$), suggesting a pronounced urban heat island (UHI) effect on air temperature is observed, coexisting with a relatively weak urban dry island effect. In contrast, the GBA, characterized by more mature and slowing urbanization, showed slower urban warming (0.123° C decade^{-1}, $p = 0.005$) compared to rural areas (0.174° C decade^{-1}, $p < 0.001$), indicating that a weakening urban dry island effect (a relative increase or lesser suppression of urban humidity over time) may exert a more dominant influence on WBT trends than the sensible heat component of the UHI.

Urban–rural WBT trends and their resulting differences are also influenced by local climate factors across Guangdong's diverse subregions. For instance, along the eastern coast, there are more comparable WBT warming trends between urban sites (0.201° C decade^{-1}, $p < 0.001$) and their adjacent rural counterparts (0.182° C decade^{-1}, $p < 0.001$), which may be explained by that sea breeze circulation may moderate local temperatures. In northern Guangdong, a mountainous region with extensive forest cover, the rural WBT warming again outpaces that observed in urban areas, with averaged urban WBT (18.20° C) being higher than the rural WBT (17.80° C).

In the GBA, characterized by advanced and mature urbanization, the average UE was −0.072° C decade^{-1} ($p < 0.001$), with the UC being the lowest among all subregions (Figure 6). This negative trend suggests that as urban centers reach advanced stages of development, urbanization ceases to be the primary driver, exacerbating the WBT difference between the city and its rural surroundings. Conversely, subregions such as the northern mountainous region and the eastern coastal region, which are still undergoing active (but not yet saturated) urbanization, generally exhibited positive or near-zero average UE and UC values. This indicates that in these developing areas, urban development continues to contribute to the observed warming of urban WBT, either by causing faster warming than in rural areas (positive UE) or by ensuring urban areas warm at least in line with regional trends (near-zero UE). The Leizhou Peninsula exhibited the highest average UE (+0.044° C decade^{-1}, $p < 0.001$) and UC (21.90%), reflecting an impact of recent urban expansion that both elevates urban WBT and accounts for a substantial portion of its overall warming trend.

To further investigate the spatial patterns underlying the aforementioned regional variations, we examined the spatial distribution of the urban–rural WBT difference under different extreme-event conditions, including non-extreme events (i.e., normal), extreme precipitation events, high-temperature events, and

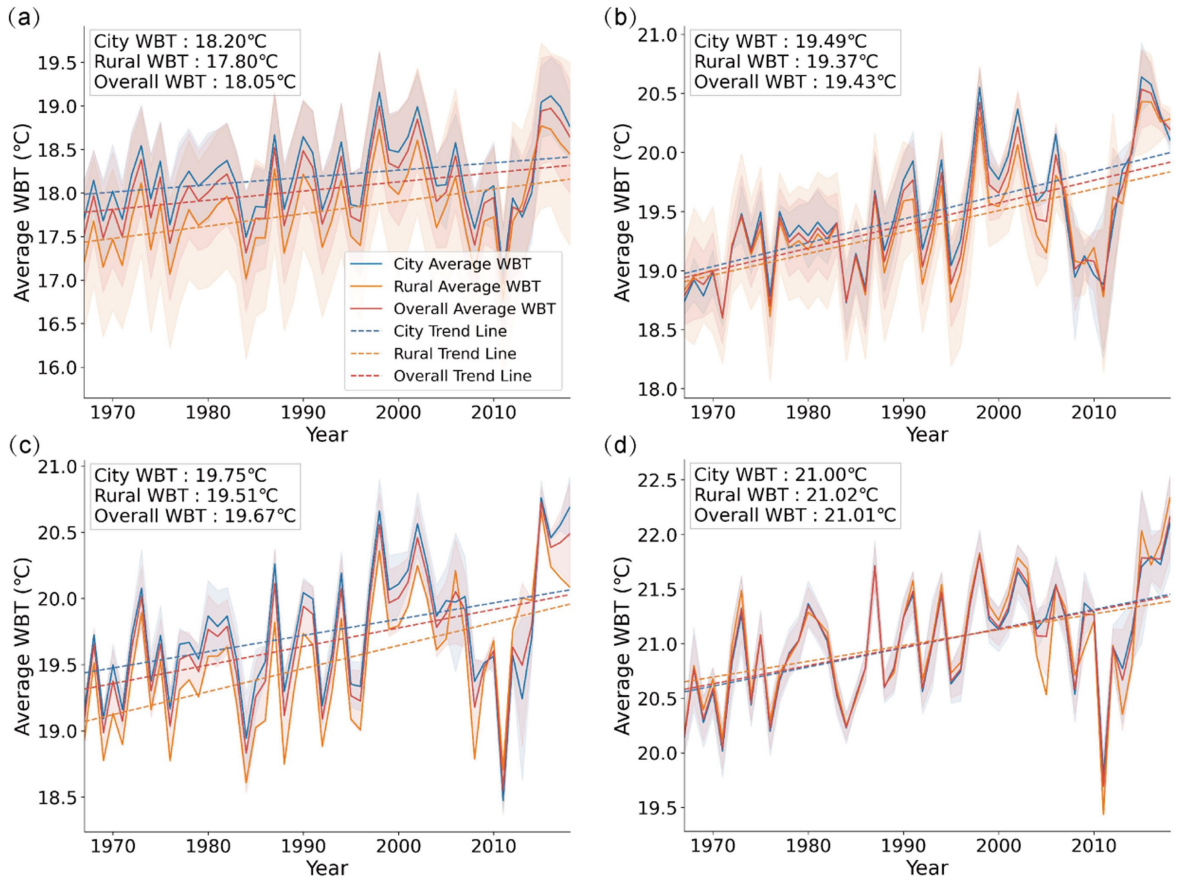


FIGURE 5
Regional time series of annual mean WBT from 1967–2018 for four subregions of Guangdong Province: **(a)** Northern mountainous area, **(b)** Eastern coastal area, **(c)** GBA urban agglomeration, and **(d)** Leizhou Peninsula. In each panel, solid lines represent the annual mean WBT for urban, rural, and all station groups, with shaded bands indicating ± one standard deviation. Dashed lines show the corresponding linear trends.

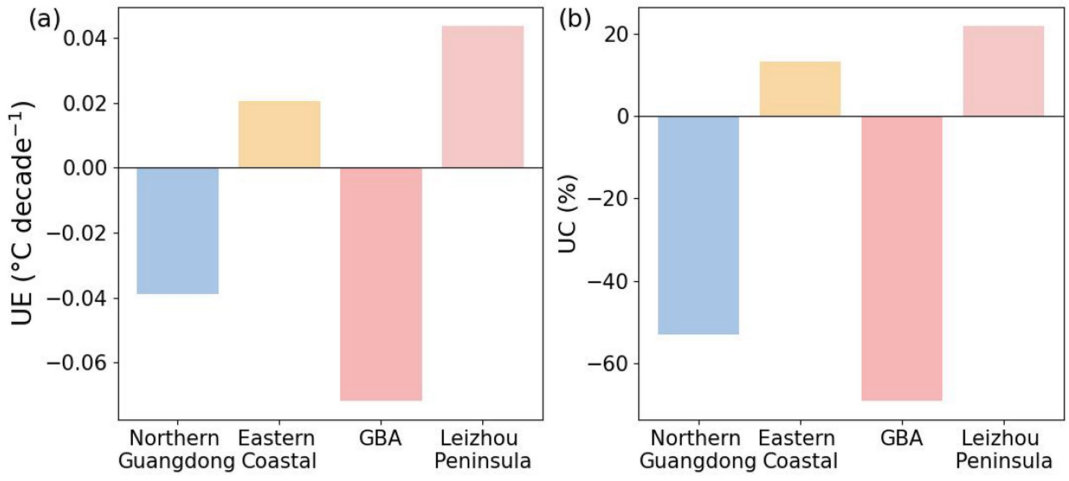


FIGURE 6
(a) Mean urbanization effect (UE; ° C decade^{-1}) and **(b)** Urbanization Contribution (UC; %) across four subregions of Guangdong Province: Northern Guangdong, Eastern Coastal area, GBA area, and Leizhou Peninsula.

compound heat-drought events (Figure 7). During periods without extreme events (Figure 7a), the urban–rural WBT difference across most of the province was modest, typically ranging between −1° C and +1° C, indicating generally weak, albeit spatially heterogeneous, urban–rural WBT differences under normal conditions. Notably, the GBA area exhibited small median WBT differences (≤1° C). In

contrast, this core was encircled by a distinct ring of significantly higher WBT differences, where values frequently exceeded 2° C, with localized peaks reaching up to 4° C.

Under extreme precipitation events (Figure 7b), the spatial pattern of the urban–rural WBT difference closely resembled that of non-event periods, with most areas maintaining a similar range of values. In contrast, both high-temperature events (Figure 7c) and compound heat-drought events (Figure 7d) generally reduced in the WBT difference across most regions. Specifically, the WBT difference often decreased, and the overall range of values narrowed from approximately 6° C during non-event periods to about 4° C. Despite the general reduction, weak positive urban–rural WBT differences (i.e., urban WBT slightly higher than rural WBT) persisted in many areas. Notable exceptions were the GBA and northern mountainous regions, where a wet-bulb cold-island effect emerged, meaning urban WBT became lower than their rural counterparts. Nevertheless, the spatial pattern remained largely consistent with that of non-event periods. The Leizhou Peninsula exhibited an increase in its urban–rural WBT difference (by approximately 0.5–1.0° C) during both high-temperature and compound heat-drought events. This might be due to localized topographic and climatic factors on the peninsula partially counteracting the broader suppressive impact that high ambient temperatures typically exert on the urban–rural WBT differences.

3.4 Influence of extreme events on urban–rural WBT differences

3.4.1 Effects of heat-related events

During high-temperature (Figure 8a) and compound heat-drought events (Figure 8b), $EUC\Delta R$ values in most regions of Guangdong are predominantly negative (Figures 9a,b), indicating a significant reduction in the urban–rural WBT difference compared to non-event periods. Spatially, the GBA and northern mountainous regions emerge as primary zones exhibiting strongly negative WBT difference, with $EUC\Delta R$ extremes falling below −3. These negative values signify a pronounced reversal where the urban WBT drops below the rural WBT. This negative difference reaches a magnitude more than three times greater than the positive urban–rural difference typically observed during non-event periods. Correspondingly, in these locations, the urban–rural WBT difference commonly shifts from a positive range during normal periods (e.g., urban 0–1° C warmer) to a negative range (e.g., urban 0–1° C cooler), forming distinct wet-bulb cold islands. Conversely, the Leizhou Peninsula and eastern coastal areas consistently exhibit $EUC\Delta R$ values greater than 1, with local maxima even exceeding 3. This finding points to a strong amplification effect during heat-related extreme events, wherein the warming of urban areas relative to their

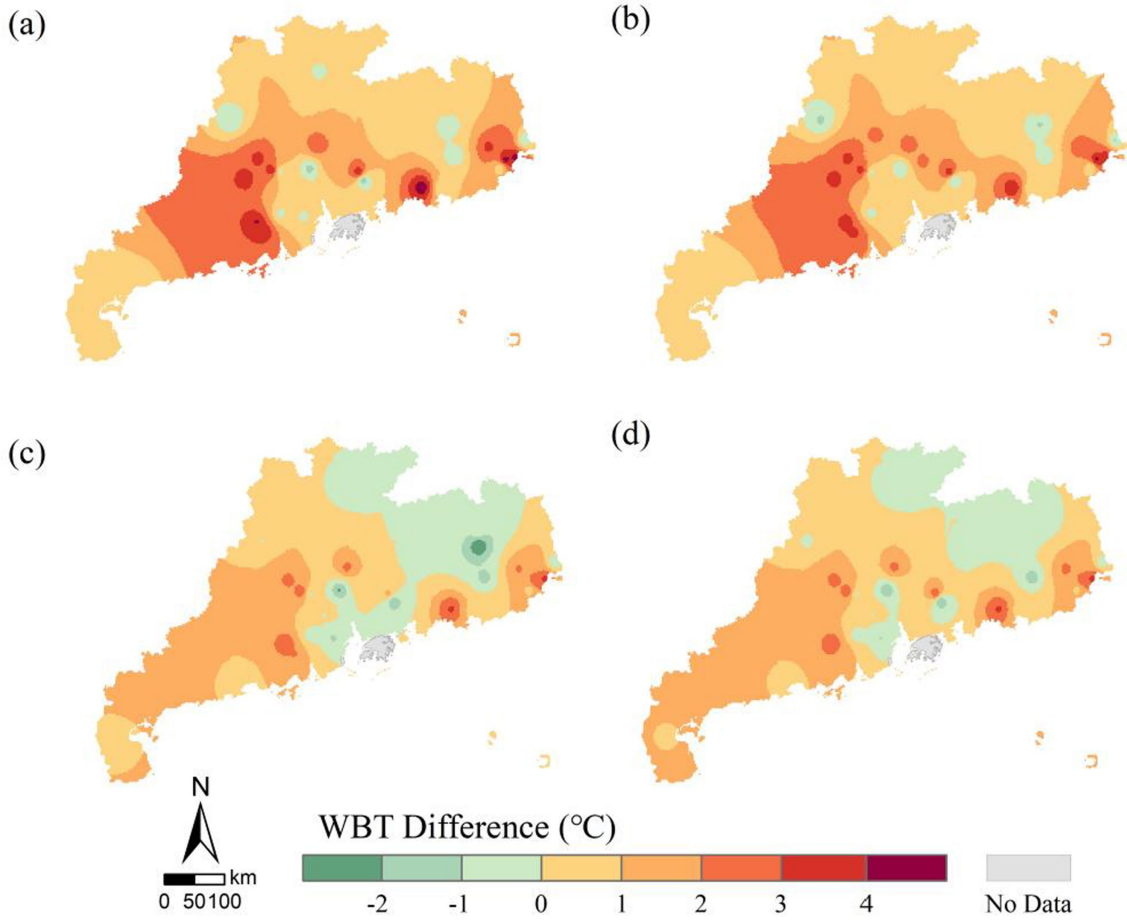


FIGURE 7
Spatial distribution of the median urban–rural WBT difference under different extreme-event conditions: **(a)** non-extreme periods; **(b)** extreme precipitation events; **(c)** high-temperature events; and **(d)** compound heat-drought events.

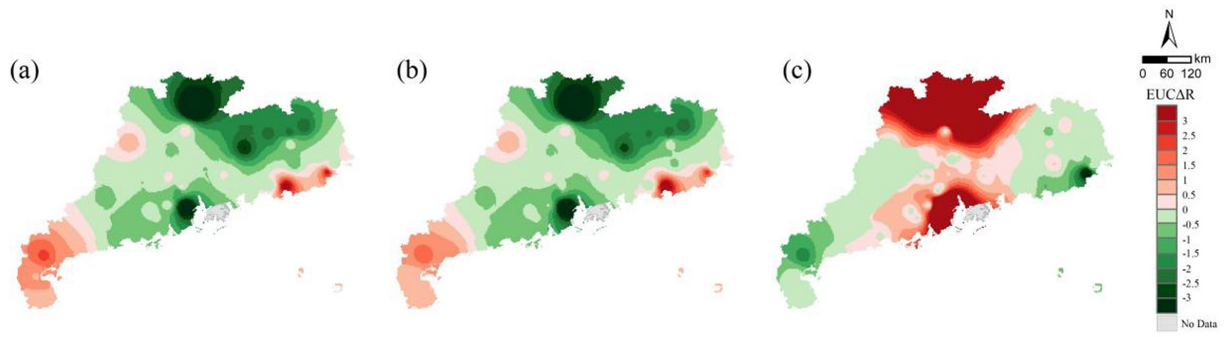


FIGURE 8
Spatial distribution of the Extreme Urban-Countryside Change Ratio (*EUCΔR*) for three different extreme events: **(a)** compound heat-drought events; **(b)** high-temperature events; and **(c)** extreme precipitation events.

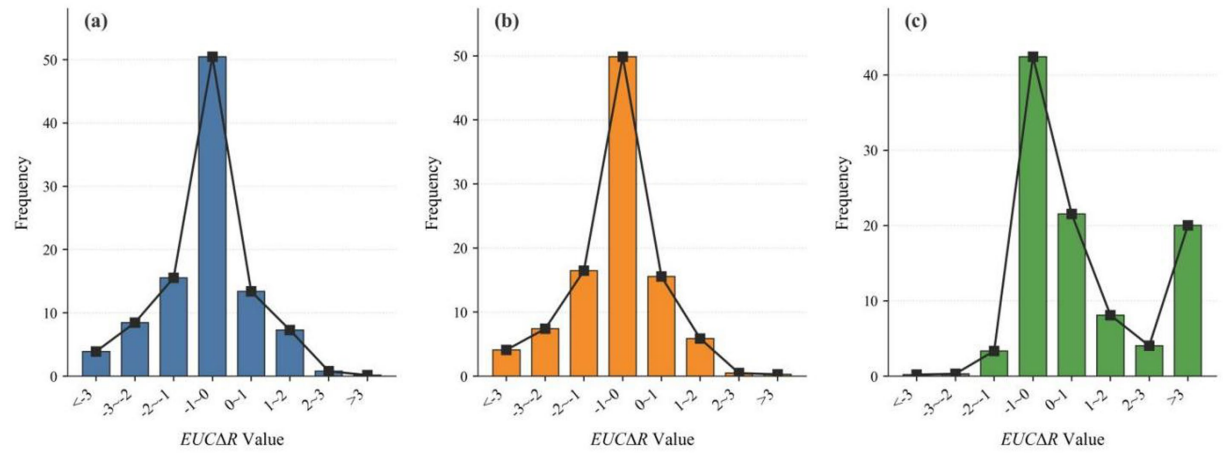


FIGURE 9
Frequency distribution of the *EUCΔR* for different extreme events: **(a)** high-temperature events; **(b)** compound heat-drought events; and **(c)** extreme precipitation events.

rural surroundings is significantly exacerbated compared to non-event conditions.

During heat-related extreme events, a negative *EUCΔR* value typically occurs when the WBT increase in urban areas is less pronounced than in the corresponding rural areas, thus reducing the urban–rural WBT difference. The spatial consistency in *EUCΔR* patterns between compound heat-drought events and high-temperature events alone suggests that extreme heat is the dominant driver of changes in the urban–rural WBT differences in humid subtropical regions like Guangdong. The additional influence of the drought component of compound events appears to be secondary.

3.4.2 Effects of extreme precipitation events

Extreme precipitation events induced fundamentally different spatial patterns of the urban–rural WBT difference, often leading to a partial or complete reversal of the effects observed during heat-drought and high-temperature events (Figures 8c, 9c). During these precipitation events, the overall *EUCΔR* values showed a noticeable shift towards positive values, generally indicating an enhancement of the urban–rural WBT difference across most regions.

Notably, the regional responses in *EUCΔR* exhibited a near-complete inversion compared to heat-related events. For instance, Northern Guangdong and the GBA, which previously showed negative *EUCΔR* during heat extremes, become zones with high positive *EUCΔR* values (peaks >3) during extreme precipitation. Conversely, the Leizhou Peninsula and eastern coast, which experienced amplified urban–rural WBT differences (*EUCΔR* > 1) during heat events, transition to zones with negative *EUCΔR* (minimums < −3) under extreme precipitation. Although both urban and rural humidity levels increased during these events, urban WBTs increased more substantially in the GBA and northern regions, whereas coastal areas showed greater rural increases.

4 Discussion

4.1 Impacts of urbanization on the spatial heterogeneity of urban–rural WBT differences

Our findings reveal that urbanization's impact on the urban–rural WBT difference is dependent on the stage of urban development, leading to significant spatial heterogeneity. In regions undergoing active urbanization, such as eastern Guangdong, a positive UE was

observed, indicating that urban WBT is warming faster than in the surrounding rural areas. This is consistent with the urban heat island effect, where urbanization alters the hydrothermal properties of the surface by increasing temperature (Wu et al., 2019).

In contrast, in mature, highly urbanized centers like the GBA core, we found a negative UE, indicating that urban WBT is warming more slowly than in the countryside. This reflects a transition from a heat-island-dominated system to one where the urban dry island effect becomes more influential. In these advanced stages, the vast expanses of impervious surfaces and loss of vegetation lead to significant reductions in urban relative humidity and suppressed evapotranspiration (Luo and Lau, 2018; Pyrgou et al., 2020). This finding is corroborated by the observed long-term decrease in relative humidity across the GBA (Lin et al., 2020), where the urban dry island effect has been strengthening (Luo et al., 2022). The cooling influence of this reduced humidity on WBT can eventually outweigh the warming influence of the UHI (Du et al., 2019), causing the urban–rural WBT difference to narrow. In contrast, rural areas maintain higher humidity levels through sustained evapotranspiration, thereby experiencing a more pronounced rise in WBT as background temperatures increase (Du et al., 2016; Jiang et al., 2019).

4.2 Extreme event modulation of urban–rural WBT differences: divergent responses to heat, drought, and precipitation

High-temperature and compound heat-drought events generally reduce urban–rural WBT differences in GBA and northern mountainous areas, sometimes even leading to the emergence of wet-bulb cold island. Conversely, the Leizhou Peninsula and eastern coastal areas show enhanced urban–rural WBT differences, while extreme precipitation exhibits opposite spatial patterns. Moreover, the consistent effects of high-temperature and heat-drought events indicate that drought's regulatory role in humid thermal environments is relatively limited.

Under high-temperature and heat-drought conditions, both urban and rural areas experience elevated air temperatures. However, changes in the urban–rural WBT differences primarily stem from the differing evaporative capacities of urban versus natural surfaces. In rural regions, the abundance of natural surfaces allows for gradual soil moisture release that helps maintain relatively higher air humidity (Luo et al., 2021). This leads to a more pronounced increase in WBT compared to urban areas, where high proportions of impervious surfaces result in lower baseline humidity (Du et al., 2019; Hao et al., 2018; Hao et al., 2023; Ward et al., 2016) and thus smaller WBT rises. This contrast is particularly evident in regions such as the GBA, where high impervious surface coverage makes urban areas significantly drier than their surroundings, and in the northern mountainous areas, where extensive forests maintain near-surface humidity through sustained transpiration during heat events. In both cases, these contrasting land surface conditions lead to a greater increase in rural WBTs.

The effect of precipitation on WBT is complex. For instance, recent studies using global gridded products and General Circulation Models found that light rain can exacerbate humid heat by increasing near-surface humidity with only a minor reduction in solar radiation, especially over arid and semi-arid regions (Zhang et al., 2024). Our study investigates extreme precipitation in a humid region, where the balance between radiative cooling and humidity enhancement varies, a dynamic that appears to be mediated by the land surface. During extreme precipitation events, as both urban and rural areas approach saturation, this land surface dependence becomes critical, particularly the difference in drainage efficiency. This reveals a paradoxical relationship in our humid region where heavy rainfall, despite its cooling effect on air temperature, may exacerbate moist-heat stress. In urban areas, the prevalence of impervious surfaces leads to rapid runoff (Miao and Tang, 1998), yet the retained surface water keeps humidity levels high (Ramamurthy and Bou-Zeid, 2014). This massive spike in local humidity may overwhelm the drop in air temperature, increasing the WBT and perceived thermal stress, to which human thermoregulation is highly sensitive (Raymond et al., 2020). In contrast, rural areas benefit from vegetation interception and swift soil infiltration (Dai et al., 1999; Zhou et al., 2009), which limits the proportion of water available for evaporation (Hao et al., 2018) and results in a relatively smaller humidity increase. Consequently, this divergence amplifies the urban–rural WBT difference, particularly in the GBA and northern regions, where urban WBTs rise more sharply.

Interactions between coastal land-sea breezes and urban systems further influence urban–rural WBT difference, with studies showing that urban-coastal microclimates can be confounded by complex interactions that favor hot-wet compound occurrences (Ganguli and Merz, 2025). For instance, during heat-drought events, sea breeze advection along the Leizhou Peninsula and the eastern coast can partially mitigate drought-induced humidity losses (Du et al., 2004) and reduce the urban–rural humidity gradient. Nevertheless, enhanced urban heat island effects in these coastal zones tend to increase the WBT differences. Under extreme precipitation, as relative humidity approaches saturation in both urban and rural areas, the modulating influence of the sea breeze diminishes. Additionally, turbulent mixing during typhoons or severe convective storms accelerates air exchange between urban and rural areas, reducing both temperature and humidity gradients and thereby narrowing the WBT differences.

4.3 Limitations and future work

The interaction between urbanization and extreme climate events is fundamentally complex and nonlinear (Zhao et al., 2021; Chen H. P. et al., 2024; Chen Y. et al., 2024). The UE and UC provide first-order estimates of the urbanization signal in station-based records (Zhong et al., 2024), while the $EUC\Delta R$ offers a normalized measure of how extreme events alter the urban–rural WBT difference. It should be noted that these metrics are designed as diagnostic tools to capture the net outcome of such complex interactions, rather than to unravel the underlying nonlinear physics. This inherent limitation underscores that our approach is not a substitute for mechanistic modeling studies (e.g., Zhao et al., 2021), but rather complements them by providing an essential observational benchmark that quantifies the real-world magnitude of these interactions and reveals their spatial heterogeneity.

The spatial representativeness of this study is somewhat constrained by the uneven distribution of urban and rural stations. While urban stations are predominantly concentrated in the GBA, rural stations are mainly situated in northern Guangdong. As a result, some rural stations could not be paired with urban counterparts, and certain urban stations lacked nearby rural stations for comparison. This spatial imbalance may impact the representativeness of the UE and UC indicators, potentially affecting the generalizability of the regional analysis.

Furthermore, our station-based approach cannot resolve the fine-scale spatial heterogeneity of WBT. Future research should leverage high-resolution meteorological grid data and atmospheric models (e.g., Weather Research and Forecasting model with an urban canopy scheme) to overcome the above limitations. Such an approach would allow for a more detailed analysis of the thermodynamic and dynamic processes at the sub-city scale, enabling a clearer attribution of the mechanisms driving WBT changes during and after extreme precipitation events.

5 Conclusion

This study investigates how urbanization and extreme events combine to affect WBT dynamics in the humid Guangdong Province. Using five decades of meteorological data from paired urban–rural stations, we show that the urban–rural WBT difference is controlled by a complex interaction between the stage of urbanization and the type of extreme weather event.

Urbanization's influence on urban–rural WBT difference is stage-dependent. Initially, the urban heat island effect typically widens these WBT disparities (an average rate of 0.0027° C decade^{-1}). However, in mature urban cores, such as within the GBA, the emergence of urban dry island effect can reduce local humidity and subsequently narrow the urban–rural WBT difference gap. Furthermore, extreme events significantly alter these patterns. High-temperature and compound heat-drought conditions tend to diminish or even reverse the urban–rural WBT difference in many urban interiors, while enhancing this difference in certain coastal regions like the Leizhou Peninsula. In contrast, extreme precipitation events often enhance urban humidity retention, generally leading to an amplification of urban–rural WBT differences and a reversal of the spatial response patterns seen during heat-related extreme events. These complex interactions underscore the regulation of wet-heat stress by the stage of urbanization, prevailing hydrothermal feedback mechanisms, and regional geo-climatic conditions, highlighting the need for further research into their coupled effects.

This study used Guangdong Province, including the GBA, as a representative example of rapidly urbanizing humid regions. It provides insights into the impacts of extreme events under ongoing global urbanization, particularly within megacity clusters and other densely populated 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

SH: Conceptualization, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. ZS: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. GC: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing. YH: Investigation, Writing – review & editing. ZD: Investigation, Writing – review & editing. SL: Investigation, Writing – review & editing.

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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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How biodiversity conservation adapts to climate change: from a cross-spatial scale framework

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Climate change has emerged as one of the most significant threats to global biodiversity, and climate adaptation has become a critical component of biodiversity conservation. This paper reviews adaptive management strategies for enhancing biodiversity resilience under climate change, based on a cross-scale framework. The findings reveal that: (1) Biodiversity conservation adaptation to climate change requires a cross-spatial scale framework, which highlights the vertical interaction and interdependencies between regional, landscape, and site-level strategies. (2) Adaptive management strategies vary across spatial scales. At the regional scale, dynamic planning based on assessment and monitoring is prioritized. Landscape-scale initiatives emphasize protected areas as the core, expanding their scope while restructuring networks through corridors, stepping stone, habitat matrix permeability, and climate refugia. At the site scale, efforts focus on *in situ* and ex situ conservation of keystone species, along with real-time monitoring of invasive species. (3) Future challenges in biodiversity conservation under climate change may include social inequity in adaptation efforts, delayed responses in dynamic landscape conservation planning, disruptions to species's ecological networks, barriers to interdisciplinary collaboration, and insufficient attention to human-climate interactions. By highlighting the differential application of adaptation strategies across spatial scales and underscoring the critical importance of cross-scale collaboration, our findings provide important insights for advancing research and practice in biodiversity adaptation to climate change, offering a theoretical foundation and practical guidance for developing multi-level, operable climate-adaptive conservation policies.

KEYWORDS

climate change, biodiversity, adaptation, region-landscape-site scale, cross-spatial scale

1 Introduction

Global climate has changed more rapidly since 1950 than in any comparable period during the preceding million years (Stocker et al., 2013). Anthropogenic climate change now represents the most significant threat to biodiversity, significantly impacting species' phenology, distribution and abundance, and further affecting ecosystem structure, function, stability and their feedback regulation to climate change (Urban, 2015). Climate change exerts profound and multidimensional pressures on biodiversity through interconnected pathways. Rising temperatures are triggering large-scale species redistribution, with many organisms shifting poleward and upward in elevation to track suitable climates (Pecl et al., 2017). Alarmingly, current extinction rates now exceed background rates by 100–1,000 times, with

projected species losses of 5% at 2 °C warming and 16% at 4.3 °C (Bongaarts, 2019). Concurrently, climate-driven ecosystem degradation manifests through cascading effects: at 1 °C warming, mass coral bleaching becomes widespread (IPCC, 2002); a 2 °C increase severely disrupts most European ecosystems, drastically reducing Mediterranean plant diversity (Bakkenes et al., 2006); and beyond 3 °C, extensive forest loss is expected across Eurasia, eastern China, Canada, and the central U.S. (Scholze et al., 2006). The cumulative impacts are compounded by extreme events, as exemplified by Cyclone Idai, which reduced small herbivore populations in Mozambique by 28% within 20 months (Walker et al., 2023). Amid escalating extinction risks and ecosystem destabilization (Field et al., 2014), climate-resilient biodiversity conservation has become a global priority. The 2024 Convention on Biological Diversity (COP16) highlighted "climate change" and "biodiversity governance" as key agenda items (Climate-Diplomacy, 2024). Given that climate change exacerbates risks to both natural and human systems, advancing scientific understanding of its impacts on biodiversity and developing adaptive conservation strategies hold critical theoretical and practical significance for global biodiversity protection and international policy implementation.

Keeping track of research and practice on biodiversity adaptation to climate change will help us identify effective strategies. Over the past two decades, scientists have conducted a systematic reviewing of adaptation strategies proposed in existing research. Since Heller and Zavaleta (2009) comprehensively reviewed relevant research from 1975 to 2007 and categorized adaptation strategies (Heller and Zavaleta, 2009), McLaughlin et al. (2022) further traced research from 2007 to 2017 and found that, in comparison, climate change refugia, climate-adaptive assisted migration, and climate-adaptive genetics are three of the most latest and robust strategies for coping with climate change (McLaughlin et al., 2022). (iii) There are also reviews for a particular adaptation strategy, such as climate change adaptation planning for biodiversity conservation (Watson et al., 2012), land-use planning-based climate change adaptation (Schmitz et al., 2015), spatial planning for climate change adaptation (Reside et al., 2018), and habitat connectivity (Keeley et al., 2018). Nevertheless, biodiversity adaptation to climate change is a systematic process, reviewing existing research and practice based on an integrated framework is necessary. For example, Mawdsley et al. (2009) constructed an integrated framework for a taxonomy of natural resource management actions, and applied it to review existing research on biodiversity adaptation to climate change (Mawdsley et al., 2009).

The existing reviews have provided important inspiration for this paper, but it must also be realized that merely reviewing biodiversity adaptation strategies is not enough. An adaptation strategy may be applicable at the national or local government levels, but is too broad for protected areas (PAs), parks, watersheds, etc. In comparison, adaptation strategies that work for one particular species may be too granular for the landscape scale. Based on the above, current reviews of climate adaptation strategies remain overly generalized, and that it is essential to review and assess existing research and practice at different spatial scales. How can adaptive management strategies across multiple spatial scales effectively enhance the adaptive capacity of biodiversity to climate change? In contrast to approaches that classify conservation actions either by type (e.g., legal policies or direct species management) (Mawdsley et al., 2009) or by the nature of the strategy itself (e.g., modifying conservation plans) (Heller and Zavaleta, 2009), this paper establishes a multi-scale analytical framework for biodiversity adaptation to climate change based on landscape ecology, systematically reviewed the adaptive management strategies of biodiversity at different spatial scales of region-landscape-site, with a specific focus on synergistic interactions among three critical scales (regional, landscape, and site) to enhance ecological resilience. Furthermore, we systematically synthesize existing research and practical interventions in climate-adaptive biodiversity conservation across these scales, while identifying key challenges for future research.

2 Adaptation of biodiversity to climate change cross spatial scales

Based on the scale-dependence hypothesis (Chase et al., 2018), this study systematically identifies core adaptive management components across regional, landscape, and site scales under the guidance of landscape ecology and existing theoretical research. On this basis, a cross-scale biodiversity adaptation framework was constructed. The framework was preliminarily validated using the Delphi method and further applied in typical practical cases to examine its explanatory power and applicability (Figure 1).

2.1 Adaptation as a continuum of resistance, resilience and transformation

The systematic conceptualization of biological adaptation originates in Darwin's theory of natural selection (1859), which emphasized organisms' development of adaptive traits through genetic variation and environmental selection pressures (Darwin, 1859). Autonomous adaptation initially manifested through evolutionary responses to natural selection, exemplified by beak morphology changes in Galápagos finches (Grant and Grant, 2002). In the early 20th century, adaptation theory expanded to include niche differentiation and coevolution, such as the Red Queen hypothesis (Valen, 1973), though remaining confined to natural ecological processes. MacArthur and Wilson's (1967) theory of island biogeography significantly advanced understanding of species adaptation mechanisms (MacArthur and Wilson, 1967), laying foundations for conservation biology. The 1990s marked a pivotal transition period in which adaptation evolved into a cross-disciplinary policy instrument through the First Assessment Report by the Intergovernmental Panel on Climate Change (IPCC) and the United Nations Framework Convention on Climate Change (UNFCCC) (IPCC, 1990; UN, 1992), extending its application to disaster management, political ecology, rights protection, and food security (Smit and Wandel, 2006). While long considered as a component of ecological resilience, adaptation's formal integration into mainstream biodiversity conservation frameworks occurred in the early 21st century. A critical turning point emerged with the 2010 Strategic Plan for Biodiversity (CBD, 2010), which for the first time explicitly incorporated adaptation into biodiversity conservation policies. Building upon this foundation, the IPCC Sixth Assessment Report (AR6, 2022) advanced the conceptual framework by proposing a "resistance-recovery-transformation" adaptation continuum (IPCC,

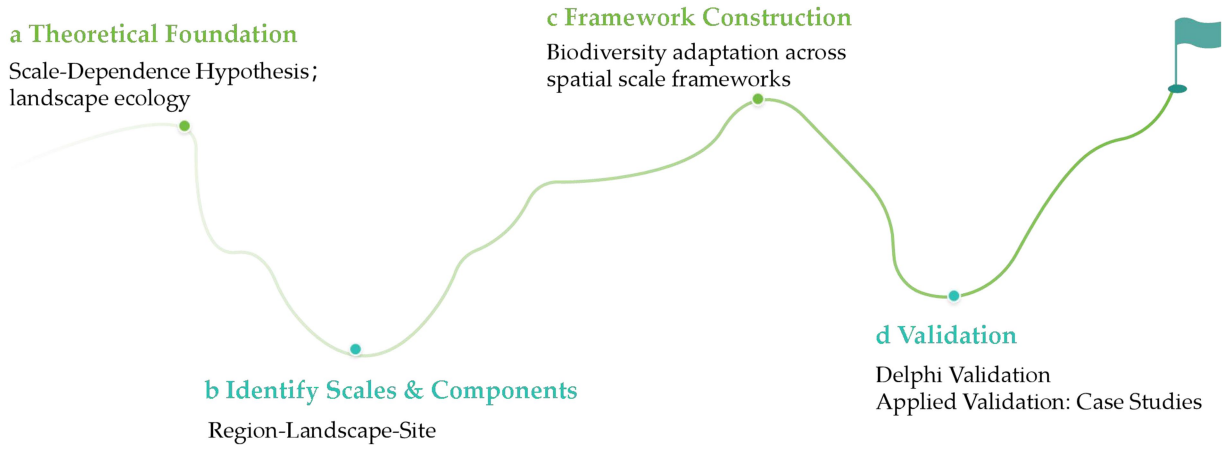


FIGURE 1
Flowchart of the analytical framework development process.

2022), systematically emphasizing the critical role of proactive human intervention in biodiversity conservation.

In contemporary conservation biology, the adaptation concept has evolved from its initial focus on innate species adaptability (MacArthur and Wilson, 1967) to policy-driven proactive strategies (CBD, 2010; IPCC, 2022) addressing anthropogenic climate impacts on biodiversity. This evolution marks a paradigm shift from studying natural ecological process to governing socio-ecological system (Sgrò et al., 2011). As biodiversity adapts to climate change, adaptation can be viewed as a continuum of resistance, recovery, and transformation, where resistance refers to the maintenance of the existing state from climate disturbances, while recovery is the process of returning to a state that was previously maintained after disturbance (Hodgson et al., 2015), and transformation means enabling or facilitating the transition to new conditions (Peterson St-Laurent et al., 2021). Policy interventions should account for ecosystem characteristics to enhance biodiversity's capacity to recover from rapid climate change while maintaining ecological functions.

2.2 Biodiversity adaptation across spatial scale frameworks

Climate change impacts on biodiversity manifest through distinct scale-dependent processes (Ackerly et al., 2010). These impacts are simultaneously determined by macro-scale climate change patterns and mediated through species-ecosystem interactions (Wu and Li, 2006), necessitating an integrated cross-scale approach to biodiversity adaptation strategies (Phillips et al., 2025; Willis and Bhagwat, 2009). Cross-scale biodiversity adaptation refers to the multi-tiered conservation responses across spatial scales (regional, landscape, and site levels) in the context of climate change (Poiani et al., 2000), designed to address climate impacts operating at multiple scales. Landscape ecology offers the foundational theoretical framework for understanding these cross-scale interactions: (i) The spatial heterogeneity and diversity theory emphasizes the non-uniform distribution of landscape elements and their influence on ecological processes. Under climate change, biodiversity conservation targets similarly demonstrate marked spatial heterogeneity. (ii) The hierarchical patch dynamics paradigm conceptualizes ecosystems as dynamic mosaics of multi-level patches interconnected through ecological processes (Zhang et al., 2013). This hierarchical structure necessitates conservation strategies that establish cross-scale feedback mechanisms, where regional climate patterns influence landscape-scale habitat distribution, while site-specific microhabitat conditions reciprocally modulate local climatic features.

Figure 2 illustrates an operational (though imperfect) framework illustrating biodiversity adaptation across three spatial scales. Specifically: (i) The regional scale encompasses broader geographical areas containing multiple landscape types (Ekroos et al., 2016). (ii) The landscape represents habitat complexes with environmental gradients supporting multiple populations (Poiani et al., 2000). (iii) The site scale refers to homogeneous habitat patches supporting specific populations (Norris et al., 2020). In practice, regional biodiversity conservation planning needs to respond to global climate change and implement vulnerability assessments, conservation target setting, spatial project planning, and monitoring throughout implementation based on local resources and institutional capacity. The landscape scale emphasizes maximizing species and ecosystem diversity to enhance resilience. Specifically, this involves connecting PAs through corridors, stepping stones, and landscape matrix, supplemented by climate change refugia to aid species persistence and recovery, thereby enhancing the protected area network connectivity and improving landscape resilience. The site scale focuses on keystone species and invasive species, with conservation efforts prioritizing in-situ conservation while incorporating ex-situ measures; invasive species monitoring requires continuous assessment of their impacts on genetic diversity and ecosystem integrity.

The conservation initiative in Yampa River Basin in Colorado, USA, exemplifies the application of this framework (Poiani et al., 2000). Initially, conservation efforts focused on protecting rare species. Since 1986, The Nature Conservancy (TNC) has implemented measures such as riparian land acquisition and vegetation restoration, primarily to protect the globally rare *Acer negundo–Populus angustifolia/Cornus sericea* riparian forest. In the late 1990s, with improved understanding of riparian ecosystem dynamics, TNC's conservation focus shifted from a single forest type to conserving the entire riparian mosaic ecosystem, expanding conservation strategies

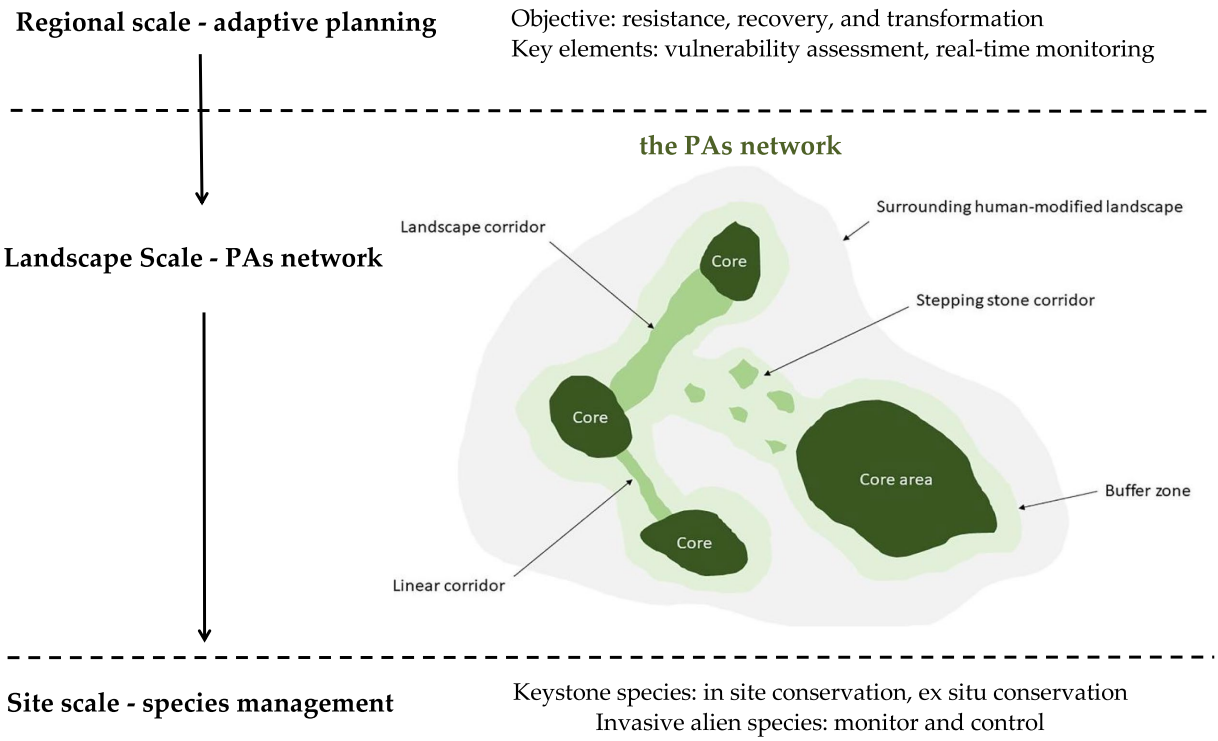


FIGURE 2
Biodiversity adaptation strategies across spatial scales. This figure was developed by the author based on existing research (Carver et al., 2021; Hole et al., 2011; Soule and Noss, 1998). The lines represent corridors, the blocks represent stepping stones and climate change refugia, and the rings surrounding the core areas, stepping stones, refugia, and corridors represent the matrix.

from the site to the landscape level. After 2010, the Yampa River Basin was incorporated into the Upper Colorado River basin-wide conservation network, realizing the "Networks of Reserves" concept.

2.3 Cross-scale synergy in biodiversity adaptation

2.3.1 How to achieve synergy?

The core of the "regional-landscape-site" cross-scale framework lies in its multi-scale systemic integration, overcoming the limitations of traditional single-scale conservation approaches to develop comprehensive solutions for climate change complexities (Figure 3). This framework emphasizes vertical interactions and interdependencies, responding to climate change uncertainties through both spatial cascades and policy implementation.

(a) In terms of spatial scales, vertical integration manifests through a species-landscape-region planning hierarchy. While site-scale species protection yields local benefits, it faces challenges in achieving broader ecosystem functional adaptation goals. Conversely, landscape-scale approaches achieve functional integration through ecological networks (corridors/refugia), yet face land-use conflicts (Mendonça et al., 2021), governance fragmentation (Dorst et al., 2022), and multi-stakeholder coordination challenges (Kauark-Fontes et al., 2023). Large-scale interventions require coordination at a broader regional scale. Scientific understanding of cross-scale adaptation challenges helps avoid maladaptive practices (Schuldt et al., 2023).

(b) In terms of implementation, vertical interaction combines top-down resource allocation and policy dissemination with bottom-up feedback mechanisms across administrative levels (Kauark-Fontes et al., 2023; Puskás et al., 2021). The goals, geographical scope, practical measures, and implementation processes of biodiversity adaptation at the region-landscape-site scales are mutually matched (Table 1). Conceptualized as an implementation cycle, climate adaptation involves four iterative phases: planning, design, implementation, and engineering management and maintenance (Mirsafa et al., 2025). Specifically: (i) The planning stage focuses on the regional level, aiming to maintain the integrity and authenticity of the regional ecosystem. This stage involves planning across broad geographical areas spanning different landscapes, including the identification and diagnosis of macro-level issues, the setting of overall adaptive goals, and the specific layout of working units and sub-projects. (ii) The design stage focuses on the landscape level, aiming to maintain the integrity of the structure and function of ecosystems. In this stage, detailed designs of working units (e.g., protected area networks) within a complex of multiple ecosystems are required, along with the formulation of corresponding specific indicator systems and standards. (iii) The implementation stage takes place at the site level, achieving dynamic balance of the matrix ecosystem through species management. Specific project construction within species habitats requires the determination of adaptive

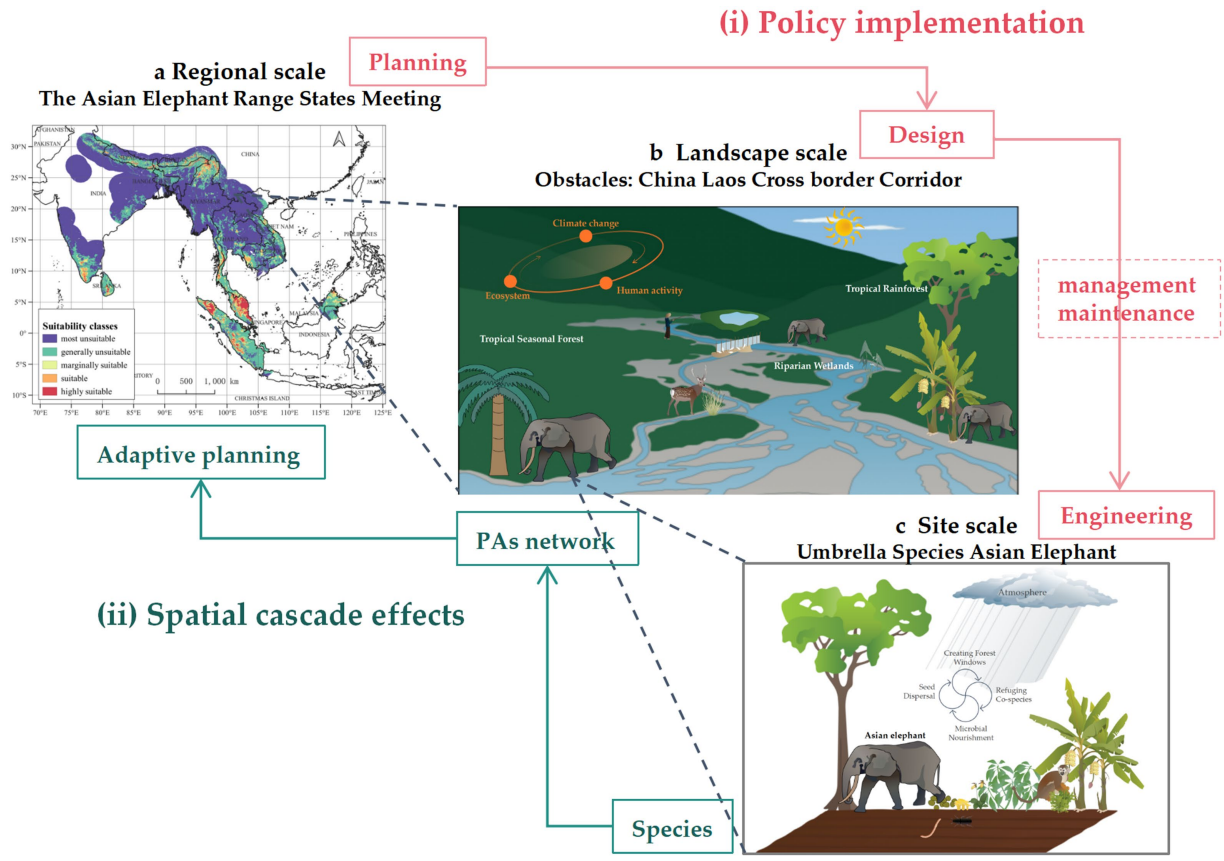


FIGURE 3
Cross-scale synergy in biodiversity adaptation strategies: Asian Elephants' dry season migration. Note: Taking the dry-season migration of Asian elephants *(Elephas maximus)* as an example, cross-scale synergy unfolds across two dimensions: (i) Spatial cascade effects. At the site scale, during the dry season, Asian elephants enhance ecosystem drought resilience by creating forest gaps. However, at the landscape scale, the China-Laos Railway fragments traditional migration corridors. Meanwhile, at the regional scale, the Asian Elephant Range States Meeting promotes corridor connectivity, facilitating climate-adaptive movements toward wetlands. (ii) Policy implementation. When droughts prolong in border regions, the regional-scale Lancang-Mekong Cooperation Mechanism coordinates hydropower water releases. Guided by transnational agreements, the landscape-scale China-Laos Railway project adopts unified ecological standards, while site-scale mitigation measures—such as extended tunnels, wildlife bridges, isolation fences, and acoustic-optical barriers—"yield" to elephants, ensuring migration pathways. Data on Asian elephant distribution across 13 range countries were sourced from Xu et al. (2024). Other graphics elements were created using the Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/imagelibrary/).

TABLE 1 **Comparison of cross scale management strategies for biodiversity adaptation to climate change.**

Scale	Objective	Geographical scope	Process	Practical measure	Examples
Region	Integrity and authenticity of the regional ecosystems	Broader geographical areas spanning different landscapes	Planning	Adaptive planning for a group of PAs network	National Biodiversity and Climate Change Action Plan 2004–2007 (Australia)
Landscape	Integrity and stability of natural ecosystems	Complex of multiple ecosystems	Design	Reconstruct PA network	the Chesapeake Bay Program; the Natura 2000 network
Site	Dynamic balance of matrix ecosystems	Habitats of homogeneous populations	Implementation	Species management	Botanical garden; Seed bank

Organized by authors.

measures based on species types and their implementation. (iv) Additionally, the management and maintenance stage covers monitoring and evaluation, adaptive management, and supervision and inspection throughout the entire process.

Biodiversity conservation across different scales works in synergy with each other and is interconnected at each level, forming a cross - scale spatial three - dimensional network to achieve collaboration.

2.3.2 Why we need synergistic integration?

The primary advantages of vertical interactions and interdependencies are reflected in the ecological linkages across spatial scales and the hierarchical transmission and information feedback mechanisms in implementation.

(a) Ecological interdependencies enable cross-scale conservation coordination, forming functional ecological networks that enhance the overall efficacy of biodiversity adaptation strategies. For instance, at the regional scale, climate models can identify refugia, providing a scientific basis for the design of corridors at the landscape scale. In turn, the construction of ecological networks at the landscape scale creates migration pathways for species conservation at the site scale.

(b) In terms of governance mechanisms, hierarchical transmission and information feedback mechanisms optimize vertical governance structures and strengthen the effectiveness of policy implementation, ensuring the scientific and operational nature of cross-scale decision-making. In horizontal cooperation, environmental departments are often the leaders in formulating national biodiversity strategy policies, while other departments (i.e., transportation, energy, waste, drainage, and water) act as supporters. Planning among departments is mostly fragmented, and policy integration always faces conflicts of interest. This leads to isolated planning and mutual buck-passing among functional departments (Kauark-Fontes et al., 2023). For example, Bicentenario Park was envisioned as a transitional space connecting the old city park and the historic center of Bogotá, Colombia. However, stakeholder coordination failures have stalled construction progress (Fixsen, 2018). Even at global scales, protracted negotiations over Convention on Biological Diversity (CBD) funding mechanisms further exemplify these governance challenges. Conversely, the Chesapeake Bay Program in the United States and the Natura 2000 network in Europe demonstrate the potential for coordinated conservation across spatial scales. The Chesapeake Bay Program guides the restoration and protection of North America's largest estuary through a regional partnership.[1] Similarly, the Natura 2000 network integrates over 27,000 PAs across member states through standardized monitoring and management frameworks.[2] These cases underscore that institutionalized cross-scale coordination is prerequisite for effective biodiversity governance.

2.3.3 Critical gaps in synergistic implementation

The critical gaps in biodiversity adaptation strategies across spatial scales are as follows:

(a) Assessment of problem-governance scale alignment. Effective cross-scale management first requires a clear distinction between the spatio-temporal scale at which problems occur (problem scale) and the institutional scale at which governance is implemented (governance scale), and an assessment of the degree of alignment between the two (Padt et al., 2014). Many countries face horizontal mismatches between internal governance scales and the scale of climate change impacts. For example, there is inconsistency between the boundaries of river basins such as the Rhine, Meuse, or Scheldt (problem scale) and the administrative boundaries of member states (governance scale) in the European Union region (Dewulf et al., 2015).

(b) Identification of ecological cascades across spatial scales. For instance, refuge planning at the regional scale needs to be coordinated with ecological corridors at the landscape scale and habitat restoration at the site scale (Phillips et al., 2025). However, there are still deficiencies in identifying and integrating ecological cascades across spatial scales (Le Provost et al., 2023; Li et al., 2025). In geographical modeling, the nonlinear characteristics of scale transformation and cross-scale interactions pose challenges to integrating multi-level ecological effects (Peters et al., 2007). For example, simple upscaling-downscaling based on traditional hierarchical theory cannot fully explain the complex interactions between different scales (Gonzalez et al., 2020; Koo, 2009). This makes it difficult to accurately predict ecosystem behavior and dynamics in cross-scale analyses, thereby limiting the synergy between conservation measures at different scales.

(c) Policy implementation via vertical integration. To match policy practice with the scale of biodiversity conservation goals, it is necessary to (i) coordinate and integrate across levels under the same objective, (ii) share information and resources within appropriate scopes, and (iii) to facilitate the resolution of cross-boundary issues by connecting governance systems at different scales. Current policy implementation not only lacks coordination across different levels of jurisdiction but also faces temporal scale mismatches. That is, adaptation strategies that require long-term implementation cycles face challenges due to the tendency to pursue short-term economic benefits under the fixed political turnover cycles of governments (Kettunen and Ten Brink, 2012). The difficulty in effectively coordinating governance needs at different scales during policy implementation affects the achievement of biodiversity conservation goals.

(d) Dynamic adaptive management. Dynamically adjusting management strategies based on multi-scale ecological monitoring data is key to biodiversity conservation. For example, the Dutch "Room for the River" program dynamically adjusts the setback distance of dikes based on annual flood simulations (Zevenbergen et al., 2015). However, there are still deficiencies in dynamic adaptive management, and the linkage mechanism between long-term dynamic monitoring and strategy adjustment has not yet been established (Zarzuelo Romero et al., 2025), which limits the flexibility and effectiveness of biodiversity adaptation strategies.

3 Regional-scale adaptation planning provides top-level design

3.1 Practices of adaptive planning

Adaptive planning provides a systematic framework for biodiversity adaptation through objective-driven resource

1 https://www.chesapeakebay.net/

2 http://natura2000.eea.europa.eu/

allocation (Reside et al., 2018). Robust regional-scale adaptive planning should incorporate the following features: reversibility, preservation of future options, resistance to a variety of impacts, and permission for mid-course adjustments (Wilby and Vaughan, 2011). Effective planning must simultaneously address multiple interacting drivers of biodiversity loss, as climate change acts synergistically with habitat degradation, soil loss, nitrogen enrichment and acidification, single-focus efforts risk exacerbating the others. For example, the Kyoto Protocol addresses emission reduction plans, the Clean Development Mechanism, carbon sequestration, biodiversity conservation and human livelihoods (UNFCCC, 1997). For adaptive planning to remain flexible and robust, assessing species vulnerability and continuous real-time monitoring are key (Sutherland, 2006).

In 2002, the Strategic Plan of the CBD called for the integration of biodiversity concerns into relevant national sectoral and cross-sectoral plans, programs and policies. Developed countries and some large developing biodiversity powerhouses have placed a high priority on adaptive planning for biodiversity to climate change. Common categories of adaptive planning include the following: (i) Integrating climate adaptation into overall national development planning, which is the choice of most countries. For example, China has consistently included ecosystems as a key area of adaptation to climate change in *A Review of China's Climate Change Policies and Actions (2022), National Strategy for Climate Change Adaptation 2035 and National Plan for Climate Change (2014–2020)*. (ii) Embedding adaptation within existing sustainability frameworks, covering sectoral domains spanning disaster mitigation, water security, public health, environmental management, energy and national security (IPCC, 2022; UNEP, 2023). (iii) Developing dedicated adaptation plans. Australia was the first country in the world to issue a dedicated action plan for biodiversity conservation, and was the first to issue National Action Plan on Biodiversity and Climate Change, which integrated conservation and adaptation of biodiversity to climate change into key strategic planning (Booth, 2012), and developed adaptation strategy in Biodiversity and Climate Adaptation in Australia.

Globally, countries are issuing biodiversity-related national strategies or plans to respond to climate change. Developed economies concentrate planning efforts on climate change mitigation, deploying highly specified and operational initiatives, while developing countries prioritize adaptation objectives (UNEP, 2023). However, economic development priorities limit developing nations to framework-level plans that remain largely conceptual, failing to address current challenges. As the most climate-vulnerable nations, developing countries require: (i) implementation of the common but different responsibility (CBDR) principle to ensure climate justice, (ii) Global Climate Change Initiative (GCCI)-type mechanisms for equitable development (Persson et al., 2009), and (iii) institutional strengthening with adequate financing. In Australia, the Council of Ministers for Natural Resource Management leads adaptive planning, while the National Institute for Climate Change Adaptation develops policy guidance tools, and the Australian Biodiversity Fund provides financial security by establishing eco-banks that implement payments for ecosystem/environmental services (PES) (Salzman et al., 2018).

3.2 Crucial components of adaptive planning

Numerous implementation frameworks for adaptive planning have been proposed in existing research and practice: the Adaptation for Conservation Targets (ACT) (Cross et al., 2012), Climate-Smart Conservation (CSC) (Stein et al., 2014), and Portfolio Decision Analysis (PDA) (Convertino and Valverde, 2013) frameworks. However, from a process perspective, biodiversity adaptation planning generally follows a cyclical "Assess-Plan-Implement-Monitor" process (Watson et al., 2012). Specifically, during the assessment phase, risk and vulnerability analyses are conducted; the planning phase develops adaptive strategies; the implementation phase implements engineering, technological, and institutional measures; and the monitoring and adjustment phase utilizes monitoring data for subsequent dynamic optimization (Abrahms et al., 2017). To maintain flexibility and robustness in adaptive planning, various analytical frameworks and tools are employed, such as Robust Decision Making (Yousefpour and Hanewinkel, 2016), Iterative Risk Management (Döll and Romero-Lankao, 2017), and Scenario Planning (Star et al., 2016). Throughout the planning cycle, understanding and assessing species vulnerability and maintaining continuous real-time monitoring are crucial (Maris and Béchet, 2010; Sutherland, 2006). Here, monitoring serves as the linchpin connecting cyclical adaptive planning by: (i) providing baseline data for pre-implementation assessment and planning design; (ii) enabling post-implementation evaluation of management effectiveness; and (iii) informing future decision-making (Williams and Brown, 2012). The interdependent relationship between assessment and monitoring is particularly noteworthy, while assessment relies on monitoring data, monitoring ultimately serves assessment needs within this iterative framework.

3.2.1 Assessing species vulnerability

According to the IPCC (2007), the vulnerability of species to climate change encompasses three dimensions: exposure, susceptibility, and adaptive capacity (IPCC, 2007). (i) Exposure refers to the degree to which species are exposed to significant climate change, such as the proportion of species in regions experiencing rapid climate change. Generally, the faster the rate of climate change and the greater its intensity and frequency, the higher the exposure of species in that area. (ii) Susceptibility indicates the degree to which species are affected by climate hazards, determined by their intrinsic biological characteristics and emphasizing the outcomes of climate change impacts, such as species extinction or reduced abundance due to climate influences. (iii) Adaptive capacity denotes the ability of organisms to adjust to, exploit, and respond to potential damages, opportunities, or consequences (McCarthy et al., 2001). The intersection of high susceptibility, high exposure, and low adaptive capacity represents the greatest vulnerability (Hole et al., 2011).

Understanding species vulnerability under a range of potential future scenarios is important due to the uncertainty in climate change projections and in species, ecosystem and human responses. On one hand, direct threats to biodiversity from climate change may include: changes in phenology, changes in species distribution shifts, community composition alterations, ecosystem function changes and loss of living space. On the other hand, human responses to climate change also have an impact on biodiversity, mainly in the agriculture, water, health and energy sectors. For example, upslope shifts in cultivation due to climate (Warner et al., 2009). Glacial retreat due to climate change is significantly

reducing dry season flows in glacial rivers, prompting the construction of upstream reservoirs to ensure adequate flows for hydroelectric power generation and downstream agricultural needs, which may reduce the diversity and abundance of organisms along the way (Vergara et al., 2007). In addition, using biofuels as an alternative resource is seen as a way to reduce greenhouse gas emissions, while crop-based biofuel production leads to the conversion of rainforests, savannas, grasslands and other natural ecosystems to agricultural land, which generates significant carbon debt and causes widespread degradation of natural ecosystems. These indirect threats can be as serious as, or even exceed in scale and scop the direct threats, while further affecting policy feasibility (Fargione et al., 2008).

Assessing species vulnerability based on this understanding of vulnerability components is an important element of adaptation planning. For understanding and reconciling the expected interactions of the various elements, Williams et al. (2008) have integrated a working framework for species vulnerability assessments, which associates the interactions between vulnerability, exposure and adaptive capacity to guide biodiversity adaptation to climate change (Williams et al., 2008). Guided by the theoretical framework, identifying interactions between vulnerability, exposure and adaptive capacity and estimating vulnerability are the next important task (Pacifici et al., 2015). Based on the consideration of species distributional changes, population changes and extinction potential (Pacifici et al., 2015), methods for assessing species vulnerability are categorized into correlative, mechanistic, trait-based and combined approaches (Table 2).

(a) Correlative approaches are the most widely used, mainly based on observed species distributional changes in relation to climate change to predict the possible future suitable distribution areas of species. Species distribution models (SDMs), in particular, emphasize data-driven projections of potential distributional shifts (Jakubska-Busse et al., 2024). Employing an ensemble of SDMs under the RCP8.5 scenario, Dawe and Boutin (2016) projected that the climatically suitable habitat of the white-tailed deer (*Odocoileus virginianus*) would expand northward across North America by 2050 (Dawe and Boutin, 2016). Dynamic vegetation models (DVMs) simulate climate-driven vegetation succession (Heffernan et al., 2024). Yu et al. (2014) coupled the LPJ-GUESS model with outputs from 19 GCMs under RCP8.5 and demonstrated that evergreen broad-leaved forests are projected to replace deciduous forests in eastern China by 2100 (Yu et al., 2014). Climate-trajectory models highlight species' capacity to persist and disperse by comparing future climatic analogues with current conditions. Ohlemüller et al. (2006) quantified the spatial extent of analogous and non-analogous climates across Europe to evaluate species' adaptive capacity under climate change (Ohlemüller et al., 2006). While correlative approaches efficiently predict future habitat suitability, their reliability is contingent upon robust model selection and high-resolution climatic data (Elith and Leathwick, 2009) and may overlook biotic interactions influencing adaptive capacity (Meier et al., 2011).

(b) Mechanistic approaches focus on quantifying the probability of extinction under climate change by explicitly incorporating species-specific traits, physiological tolerances, and habitat interactions into viability assessments. Population viability analysis (PVA) exemplifies this strategy; it integrates physiological thresholds and the stochasticity of climatic events to estimate extinction risk, with particular emphasis on endangered taxa. Using PVA, Vargas et al. (2007) demonstrated that an increase in El Niño frequency elevates the probability of population collapse for the Galápagos penguin (*Spheniscus mendiculus*) to 78% within the next 100 years (Vargas et al., 2007). Although mechanistic approaches are powerful in integrating physiological and behavioral mechanisms underlying extinction risk, they demand extensive data and remain challenging to couple with non-climatic degradation (Foden et al., 2016).

(c) Trait-based assessment (TBA) refers to assessing the potential climate change impacts on a species by identifying the population, ecological niche and habitat characteristics of individual species through literature surveys, data compilation and expert consultation (Aguirre-Gutiérrez et al., 2025). A species is considered to have limited adaptive capacity if its habitat is within a restricted elevational range, if it has low genetic diversity or if it is dependent on only a few prey or host species. Applying this framework to the world's avifauna, Foden et al. (2013) identified alpine endemics such as the Himalayan Snowcock (*Tetraogallus himalayensis*) as highly vulnerable because of their restricted altitudinal range and weak dispersal ability (Foden et al., 2013). Although TBA translates functional attributes into quantitative vulnerability scores, the weighting of individual traits requires expert calibration to minimise subjectivity.

(d) Combined approaches integrate correlative, mechanistic and TBA in a complementary manner to meet empirical needs. Pearson et al. (2014) coupled SDMs with PVA and demonstrated that dispersal barriers can trigger local extinctions of European amphibians even within climatically suitable habitats; such integration reduces predictive uncertainty, yet it demands extensive cross-disciplinary data support (Pearson et al., 2014).

3.2.2 Real-time monitoring throughout the process

Monitoring serves as a critical component of adaptive planning implementation, providing early warnings for emergent climate risks and establishing empirical bases for conservation effectiveness evaluation, with its outcomes requiring real-time integration into the planning revision process (Corelli et al., 2024). Specifically, monitoring objectives can be operationalized through three key dimensions: (i) Understanding how ecosystems, habitats, and species respond to climate change while identifying compounding stressors that may exacerbate these responses; (ii) Generating data for model development and validation to enhance predictive capacity for climate adaptation scenarios; (iii) Assessing the effectiveness of policy and management interventions (Bongaarts, 2019). As a representative case study, the European Biodiversity Observation Network (EU BON) project (2012–2017) established a continent-scale monitoring infrastructure through standardized permanent plots (accessible via https://monitoring.europabon.org), systematically recording species abundance, phenology, and microclimate data to analyze climate-land use interactions. The longitudinal datasets enabled refinement of species distribution models and evaluation of Natura 2000 PAs' capacity to accommodate climate-induced species range shifts (EU BON, 2017).

TABLE 2 Biodiversity vulnerability assessment methods.

Categories	Methods	Description	Identification	Examples
Correlative approaches	Species distribution models (SDMs)	Project future species distributions based on current distribution, abundance data and climate conditions	Sensitivity; exposure	Early and Sax (2011)
	Dynamic vegetation models (DVMs)	Process-based simulations of vegetation functional, structure and distribution under climate change	Sensitivity	Elith and Leathwick (2009)
	Climate-path models	Predict species' migration pathways by assessing populations' viability and dispersal capacity	Sensitivity.	Yu et al. (2014)
Mechanistic approaches	Population viability analysis (PVAs)	Spatially explicit modeling of population viability using species-specific demographic and environmental drivers	Sensitivity; exposure	Vargas et al. (2007)
	Ecological niche models (ENMs)	Predict extinction-risk areas based on species-habitat interactions	Sensitivity; exposure; adaptability	Morin and Thuiller (2009)
	Metapopulation models	Model distribution change for species using fragmented or patchy habitat networks	Sensitivity; exposure; adaptability	Wilson et al. (2009)
Trait-based assessment	Trait-based assessment (TBA)	Qualitative assessment of the impact of climate change on certain species	Sensitivity; exposure	Spencer et al. (2019)
Combined approaches	Assessment based on generic life history	Combine ecological niche models with demographic models	Sensitivity; exposure	Pearson et al. (2014)
	Climate Change Vulnerability Index (CCVI)	Assess regional exposure (e.g., temperature and humidity) and future changes in suitable habitat under future climate change and evaluating species vulnerability	Exposure; adaptability	Siegel et al. (2014)
	Climate Change Vulnerability Assessment (CCVA)	Evaluate extinction risk considering species' sensitivity (habitat/phenology), exposure (temperature/rainfall), and resilience (migration/ evolution)	Sensitivity; exposure; adaptability	Foden et al. (2016)
	System for Assessing Vulnerability of Species (SAVS)	Questionnaire-based assessment of climate change impacts on habitat, phenological, and interpopulation dynamics	Sensitivity; exposure	Bagne et al. (2011)

Operationalizing sustained monitoring requires the iterative execution of three core tasks: (i) Standardization of indicator systems. Standardized monitoring based on the Essential Biodiversity Variables (EBVs) enables comparable metrics across genetic, species, and ecosystem levels, facilitating cross-project data integration and trend analysis (Geijzendorffer et al., 2016). For instance, the SoilBON network employs microbial diversity and soil organic carbon EBVs to assess policy impacts on subsurface biota, with springtail (*Collembola*) abundance serving as a rapid indicator of soil quality (Guerra et al., 2021). Likewise, the Global Coral Reef Monitoring Network adopts hard coral cover, macroalgal canopy cover, and fish diversity and abundance as three robust EBVs for reef health assessment (Obura et al., 2019). (ii) Multi-scale data integration and model validation. Species, ecosystem, climatic and remotely sensed data collected at nested scales are assimilated into analytical models to enhance the resolution of interaction effects (Jetz et al., 2019). Rogers et al. (2025) integrated multi-scale data via zero-inflated Bayesian regression to quantify the joint influence of climate and land use on freshwater fish

assemblages in the northeastern United States (Rogers et al., 2025). (iii) Data sharing and attribution analysis. Scientifically rigorous designs facilitate seamless data exchange, enabling the timely detection of natural trends and extreme events while disentangling causal pathways. The Colorado Parks and Wildlife agency exemplifies this approach through the Colorado Beaver Activity Mapper, which fuses: GPS-mapped beaver dam, citizen science activity reports submitted via the Engage CPW platform, and ecological process data from interagency portals to identify the drivers of beaver–human conflict dynamics (CPW, 2025; Longwell, 2025).

Moreover, the protracted nature of climate change and the persistence of statistical noise necessitate long-term monitoring programs (Leung and Gonzalez, 2024). Most environmental time series require extended periods before underlying trends or variable relationships achieve statistical significance. Many ecological responses—including species migration and community succession—as well as cyclical climatic phenomena such as the El Niño, unfold over decades. For instance, the long-lived trees and limited seed dispersal mean that forest communities may require centuries to complete demographic turnover, whereas contemporary anthropogenic warming exceeds historical natural variability, resulting in marked lags between climatic forcing and forest response (Fastovich et al., 2025). Consequently, the informational value of biodiversity data increases exponentially with the length of time series (Robinson et al., 2005). Nevertheless, sustained biodiversity monitoring has been documented as a high-cost endeavor, with cumulative expenditures reaching the millions to billions of dollars—an issue repeatedly identified as a critical financing challenge in recent international assessments (CBD, 2024; NPWS, 2021; UNEP-MAP, 2022).

4 Reconfiguration of the network of PAs at landscape scale

4.1 Expanding the scope of PAs

The establishment of PAs continues to be the best strategy for biodiversity conservation at the global level (Bruner et al., 2001), enhancing species' adaptive capacity. According to the IUCN (2018), the global PA network comprises 238,563 sites, covering 14.9% of terrestrial and 7.3% of marine areas (Elise et al., 2018). The advantages of PAs are that they effectively enrich baseline species diversity, achieve conservation targets, promote population connectivity, and maintain genetic adaptive potential. Expanding the scope of PAs and enhancing habitat quality will enhance the ability of species to adapt to climate change in their original habitat, especially amidst increasingly frequent extreme weather events (Abernathy et al., 2019). The CBD's Aichi Target 11 explicitly incorporates PA coverage in Key Biodiversity Areas (KBAs) as a progress indicator (CBD, 2011). Climate-informed PA expansion requires five strategic considerations.

(a) Focusing on potential changes in biodiversity distribution under climate change to fill gaps. Species currently outside PA networks, particularly rare and endemic species, should receive priority protection (Rodrigues et al., 2004). Concurrently, restoring ecosystem function requires focusing on gap species' roles in reestablishing the "top carnivore-herbivore-primary producer" trophic network.

(b) Planning PAs requires considering both replication and representation. Replication entails protecting multiple samples of the same type of ecosystem or population needs to be protected in different areas; when one area is climate-affected, surviving populations in other areas can serve as reintroduction sources (Mawdsley et al., 2009). Representation involves protecting a comprehensive portfolio of PAs, such as the protection of multiple genetically variable populations of a species, different communities of an ecosystem type or multiple habitats (Giraudo and Arzamendia, 2017). A key challenge is identifying representative PAs given climate-induced ecosystem transformations and novel species assemblages.

(c) Prioritization should target areas with greater geographic and climatic diversity (S. Liu et al., 2025). Based on the principle of being the most species-rich and the most threatened, the 34 global biodiversity hotspots—covering merely 2.3% of land area but containing more than 75% of endangered mammals, birds and amphibians—demand urgent protection (Sgrò et al., 2011). Moreover, genetic diversity hotspots should also receive enhanced attention (Schmidt et al., 2024).

(d) Fully utilizing the conservation value of keystone species, indicator species, pioneer species, umbrella species and flagship species. As Chinese Academy of Sciences Academician Li Zhensheng observed, a single gene can influence the rise and fall of a nation, a single species can shape the economic lifeline of a country, and healthy ecological community can improve regional environment (CAS, 2013). The presence and abundance of these species can have a major impact on ecosystems, and if lost, a 'butterfly effect' of change throughout the ecosystem can be triggered.

(e) Selecting genotype-specific habitats for PA designation to promote *in situ* evolution of species (Dunlop and Brown, 2008), such as areas of steep ecological gradients, areas with recent significant geological or climatic changes (Cowling and Pressey, 2001), including island ecosystems (Cartwright, 2019).

4.2 Restoring landscape connectivity

4.2.1 Structural approaches to connectivity enhancement

In most cases, continuous and intact native habitats are the best solution for biodiversity conservation. However, in reality, a large number of economically or socially significant land-use types have separated PAs into ecological islands. Reconfiguring PA networks can help populations move along ecological corridors and increase population size, thus increasing adaptive resilience and improving resistance to climate change impacts. Corridors, stepping stones and matrices collectively transform scattered PAs into an interconnected network that retains a natural vegetation-like structure, forming PA networks. Linear corridors directly connect PAs through habitat patches of habitat, facilitating species dispersal (Stralberg et al., 2020b). For example, the tri-national Great Limpopo Transfrontier Conservation Area (GLTFCA) elephant-movement corridor network, completed in 2024 by South Africa, Mozambique, and Zimbabwe, provides approximately 15,000 African elephants and wildebeest with 3,500 km^2 of continuous dry-season migration habitat (Bakari, 2025). Appropriately sized stepping stone patches shorten the spatial distance

between suitable habitats and lower the energetic cost of cross-landscape movement (Schüßler et al., 2020). In the Atlantic Forest of Brazil, the Portal de Paranapanema restoration project established 90 agroforestry stepping stones (5–20 ha each) that reconnected forest fragments, restoring 1,800 ha of contiguous forest within a decade (Hilty et al., 2020). As the largest, most homogeneous, and most connected component of the landscape, the matrix plays a pivotal role in mitigating edge effects when its ecological quality is improved (Ruffell et al., 2017). Colombia's Caribbean Ecological Connectivity Initiative converted 1.5 million ha of agricultural matrix (oil palm, pasture, and urban zones) into multifunctional sustainable-use zones through zonation, integrating them with core reserves and corridors to prevent protected-area isolation (FAO and UNEP, 2020).

Corridors and stepping stones constitute essential supplements to the matrix, offering structural guarantees for species movement and the continuity of key ecological processes. However, it must be noted that:

(a) Corridor effectiveness is highly contingent upon the dispersal capacity of the focal taxa: volant birds may benefit, whereas amphibians and invertebrates often fail to use corridors that are too narrow or environmentally unsuitable. Lynch (2019) observed that contemporary urban greenway designs disproportionately cater to mammals and birds, neglecting the requirements of low-mobility species (Lynch, 2019). Moreover, Linear corridors are prone to induce edge effects, leading to abrupt changes in microenvironment parameters such as light and wind speed, and may become a diffusion pathway for invasive species (Bennett and Bennett, 2003). In experimental corridors at Savannah River Site, South Carolina, increased edge illumination significantly elevated densities of the invasive fire ant (*Solenopsis invicta*), resulting in a marked decline in native ant diversity (Resasco et al., 2023).

(b) The successful implementation of stepping stones strategies hinges on critical thresholds of patch area and inter-patch distance, and static configurations may prove inadequate under climate-driven range shifts (Huntley et al., 2008). Saura et al. (2014) argue that stepping stones must attain sufficient area or quality to yield conservation benefits (Saura et al., 2014). Empirical work on the Tianshan Mountains further demonstrated that stepping stones design parameters (size, placement, and species composition) should be dynamically adjusted to match focal species' dispersal distances (Han et al., 2022).

(c) Matrix strategies confront multiple challenges: heterogeneity management complexity, socio-economic conflicts, and differential species responses. In Queensland, Australia, despite subsidies encouraging pastoralists to retain native vegetation, the economic appeal of high-return crops such as sugarcane has hindered effective heterogeneity management, and avian community structure has shown no significant improvement (Macinnis-Ng, 2014). Whether landscape connectivity restoration enhances biodiversity resilience to climate change depends on the coupled effects of climate velocity, habitat quantity and configuration, landscape fragmentation, the overall extent and elevational gradients of corridors–stepping stones–matrix, and species dispersal capacity. Consequently, dynamically adjusting the spatial extents and areas of corridors, stepping stones, and the matrix in accordance with climate-change scenarios and species dispersal traits has become the central challenge in contemporary landscape connectivity restoration.

4.2.2 Implementation frameworks and global applications

Research and practice in restoring landscape connectivity can be divided into two categories: focal species-based and network structure-based approaches.

(a) Focal species-based connectivity, the more traditional approach, involves planning by predicting species' future distribution based on their exposure, sensitivity, and resilience under climate change (Krosby et al., 2015). Key applications includ: (i) finding habitats or corridors that will remain valuable for certain priority species even under climate change (Fan et al., 2017); (ii) predicting species distributions based on climate change, and thus determining how to protected area or promote landscape connectivity (Choe et al., 2017). Published researches have also shown passionate concerns about ecological corridor planning for flagship species such as Asian elephants and giant pandas (Mandal and Das Chatterjee, 2023).

(b) Network structure-based enhances landscape permeability by enriching the physical elements to facilitate species adaptation (Keeley et al., 2018). The specific methods can be summarized as follows: (i) Take advantage of the innate connectivity of waterways (Krosby et al., 2014); (ii) Mapping of environmental gradients based on macro-climatic gradients or land cover permeability (Rouget et al., 2006); (iii) Priority is given to the most natural areas with less human disturbance as corridors (Belote et al., 2016); (v) Design lattice-work corridor along latitudinal/longitudinal axes (Townsend and Masters, 2015); (iv) Maximize the continuity and diversity of the physical environment adjacent to the corridor (Beier and Brost, 2010).

Restoring landscape connectivity based on network structures has been incorporated into biodiversity conservation in multiple countries. Since 1992, to ensure ecological connectivity and habitat quality, The EU's Natura 2000 network (established in 1992) covers nearly 28,000 sites (18% of land area), which is at the heart of the EU's ecological conservation and climate change adaptation program (BISE, 2022). Mitigation banks in the U.A. adopt a range of strategies to conserve, manage and restore degraded habitats, connect fragmented habitats, create buffers and habitats for adaptive conservation of biodiversity (EPA, 2002). The Cape Floristic region of South Africa has a protected area plan that incorporates river corridors across mountains (Pressey et al., 2007). Australia has initiated large-scale landscape restoration and connectivity projects to combat climate change (Taylor and Figgis, 2007). In addition, countries have been developing green infrastructures to restore the connectivity between cities and nature. Green infrastructure is defined as an interconnected network of natural areas (e.g., rivers, wetlands, forests and wildlife habitats), and human-made environments (e.g., green spaces, parks, farmlands and pastures) (Canzonieri et al., 2007), the connectivity of which is essential for the survival of natural species, air and water quality, and human health and quality of life. In 2022, the EU launched biodiversity strategy for 2030, which designated "the

improvement and restoration of ecosystems and their services through the development of green infrastructure" as one of its six headline targets (EU, 2022).

4.3 Identifying climate change refugia

4.3.1 Conceptual foundations and ecological significance

Escalating frequency, intensity, and duration of extreme climatic events impose substantial physiological and demographic stress on biota (Murali et al., 2023). Climate change refugia emerge as pivotal sanctuaries for species persistence and population recovery. Unlike landscape connectivity initiatives that design migration pathways based on species traits and dispersal capacity, refugia-oriented strategies focus on safeguarding residual populations to maintain genetic diversity (Ackerly et al., 2020). Refugia are defined as spatial habitats into which populations contract when confronted with climatic stress, providing critical buffering when necessary (Morelli et al., 2020). For taxa constrained within such refugia, migration or dispersal to more suitable habitats is often precluded by intrinsic or extrinsic barriers (Poulos et al., 2013). Consequently, facilitating population persistence within refugia is pivotal for both post-extinction recolonization and long-term adaptation under climate change, rendering the identification of refugia a priority for biodiversity conservation planning.

Refugia are species- and stressor-specific, shaped by the dynamic interplay between stressors and organisms (Greiser et al., 2020; Stewart, 2010).

(a) Climate change as the dominant stressor. The velocity and magnitude of climatic shifts constitute the primary criteria for refugium identification (Szcodronski et al., 2024). If global warming is constrained to 2 °C, integrating climate-change refugia into an expanded protected-area network remains feasible (Saunders et al., 2023). For example, the U.S. National Park Service designated the meadow complex of Devils Postpile National Monument as a climate-change refugium and implemented invasive-tree removal to preserve its ecological function (Morelli et al., 2016). When warming exceeds 2 °C, however, most refugia will be restricted to high latitudes and elevations (Lawler et al., 2020).

(b) Anthropogenic co-stressors. Intensive infrastructure development, habitat conversion and degradation, poaching, and pollution—are critical co-stressors. Contemporary refugia such as nearshore coral reefs of the Great Barrier Reef show reduced survival potential due to land-based runoff driven by human activities (van Woesik, 2025).

(c) Stressor interactions. The compatibility between landscape attributes and the biophysical thresholds of refugial species is therefore essential (Keppel et al., 2024). Topography, soil type, ecosystem engineers (e.g., beavers), and microclimate modifiers (e.g., forest canopies) facilitate the formation and maintenance of climate-change refugia (Cartwright and Johnson, 2018; Frei et al., 2023; Kuntzemann et al., 2023; Stralberg et al., 2020a). Biophysical thresholds of refugial species serve as key indicators of whether a refugium effectively buffers ecosystems from climate change (Beaumont et al., 2019; Greiser et al., 2020). For instance, peat-forming bryophytes sustain hydrological feedback that maintains soil moisture, locally reducing fire and drought frequency and thereby promoting refugium formation; conversely, partial drainage or intensified drought reduces moisture retention; once critical biophysical thresholds are exceeded, the buffering capacity of climate-change refugia declines (Kuntzemann et al., 2023).

4.3.2 Technical challenges and uncertainties

Technically, climate change refuge identification depends on the accumulation of data across multiple species, such as relying on phylogenetic comparisons (Keppel et al., 2018), phylogenetic diversity metrics (Costion et al., 2015) and phylogenetic geographical analysis (Liu et al., 2025) to collect genomic data of certain species. Based on the collected species data, SDM is used for large-scale identification. Specifically, the habitat requirements, population dynamics and dispersal of a species are incorporated into bioclimatic models to predict the potential future distribution of a species at local, regional or larger spatial scales, and to identify refuge locations based on current distribution versus modelled future distribution projections (Briscoe et al., 2016). However, refugium identification confronts significant methodological, data and ecological challenges due to the complex interactions among diverse stressors, landscape contexts and refugial taxa.

(a) Uncertainty in climate models. SDMs serve as a critical tool for identifying refugia (Georges et al., 2024), yet most models primarily correlate species distributions with macroclimatic variables, failing to comprehensively incorporate key ecological factors such as soil properties, vegetation structure, hydrology, land use, invasive species, and behavioral buffering. When projecting future ranges and identifying refugia, due to truncating all acceptable conditions for species, it may encounter niche truncation challenges (Anselmetto et al., 2025), which may either over or underestimate the true location of refugia. Furthermore, SDMs exhibit delayed responses to dynamic changes. Most current approaches rely on steady-state climate assumptions, rendering them inadequate for capturing the immediate impacts of extreme events (e.g., wildfires, droughts) on refugia. For instance, studies on post-glacial oak refugia demonstrate that species migration is strongly climate-driven (Hao et al., 2023), yet existing models struggle to integrate abrupt disturbances (e.g., flash droughts) that may disrupt refugial habitats.

(b) Limitations in data acquisition across spatial and temporal scales. Data deficiencies create both taxonomic and spatial blind spots in refugia identification. Phylogenetic analyses and genetic diversity assessments rely heavily on existing genomic datasets, yet endangered species frequently lack such genetic information, compromising refugia prioritization. For instance, rare tropical rainforest plants often remain genomically uncharacterized, hindering accurate evaluation of their refugial potential (Costion et al., 2015). Similarly, the Refugia of endemic Pacific island birds have not been included in conservation plans due to genomic data gaps (Sherley, 2001).

Spatial blind spots emerge from reliance on high-resolution environmental data. Refugia identification proves particularly sensitive to spatial resolution and thermal buffering thresholds. Coarse-scale

global climate datasets (e.g., 1-km resolution) systematically underestimate fine-scale temperature variations in topographically complex terrain, causing omission of critical microrefugia (e.g., ravines, caves) (Rosauer et al., 2013). Furthermore, the paucity of high-resolution environmental data in tropical, deep-sea, and polar regions biases identification efforts toward well-studied areas, leaving many potential refugia undetected (Morelli et al., 2020).

(a) Stressor-species interaction gaps. Most studies focus on flagship species while neglecting community-level interaction dynamics, including competitive interactions among plant species, plant–animal relationships (herbivory, pollination, seed dispersal) (Ackerly et al., 2020); anthropogenic pressures (e.g., trawling impacts on marine refugia, deep-sea mining effects) (Zelli et al., 2025). Climate-human pressure interactions may drive species reassembly and loss, potentially altering ecosystem functioning and potentially unbalancing refugium network design (González-Trujillo et al., 2024).
(b) Dynamic threshold uncertainty. Microclimatic stability thresholds differ among refugial species and even among life-history stages within the same species, yet these biological thresholds often defy clear identification (Hillebrand et al., 2020) and quantitative characterization (Groffman et al., 2006). Critical knowledge gaps persist regarding the biological threshold at which refugial processes lose their buffering capacity against climate change impacts (Costa et al., 2022).

5 Site scale emphasis on species

5.1 *In situ* and ex situ conservation for keystone species

In 2023, the IUCN released its latest Red List of Threatened Species, assessing 157,190 species, of which 44,016 are threatened with extinction (IUCN, 2023), highlighting the urgency. In situ conservation is one of the most effective methods for promoting the population recovery of keystone species, yet accelerating climate change has caused protected-area boundaries increasingly to misalign with shifting climatic envelopes, producing a pronounced spatio-temporal mismatch (IPCC, 2022). The first global assessment revealed that, among 11,633 terrestrial vertebrate species examined, 1,424 (12.2%) are unprotected gap species (Rodrigues et al., 2004), thus necessitating ex situ measures as a supplement. While ex situ measures can immediately avert acute threats for species unable to persist on site, they often do so at the expense of ecological context and evolutionary feedback (Minteer, 2014; Seddon et al., 2014). Integrating dynamic *in situ* management with ex-situ interventions to create a "parallel situ conservation" may mitigate mismatch risk while preserving ecological integrity (Feng et al., 2023).

5.1.1 In situ conservation for keystone species is the optimal choice

For keystone species, in situ conservation is one of the most effective ways to reduce the biodiversity loss on a global scale. The specific implementation is divided into three steps:

(a) Using data on species richness, endemism, species threatened, taxonomic distinctiveness and habitat uniqueness to varying degrees to identify keystone species based on vulnerability and irreplaceability (Cottee-Jones and Whittaker, 2012).
(b) Identifying KBAs on the basis of the previous step and four criteria: threatened species and ecosystem types, geographically restricted biodiversity, ecological integrity, and biological processes (Langhammer, 2007).
(c) Ultimately, gradually implementing in situ conservation programs for different types of KBAs, such as biodiversity hotspots, plant diversity centers, endemic bird areas, and most valuable ecological areas (Bonn et al., 2002).

Thanks to international efforts, 14% of forests (Schmitt et al., 2009) and 88% of vertebrate species (Rodrigues et al., 2004) have been protected in 34 biodiversity hotspots around the world, and in situ conservation of species has been actively promoted. However, half of the world's KBAs are still unprotected (Butchart et al., 2012). In addition, in situ conservation on the site scale has difficulty maintaining good ecological processes because of inadequate management effectiveness and the isolation of PAs from each other, and the loss of biodiversity at the population level is often prone to far-reaching ecological and evolutionary consequences, such as the loss of top predators. Under land use pressure, in situ conservation faces the enormous challenges of feeding 9 billion people by 2050 and biodiversity conservation.

5.1.2 Ex situ conservation aids retention of endangered species

Endangered species are more susceptible to climate change and there are climate thresholds beyond which the probability of extinction increases dramatically, thus making ex situ conservation an important initiative for the adaptive management of endangered species (Solomon et al., 2007). Ex situ conservation refers to the relocation of plants, animals and other organisms from areas that have become unsuitable to other areas that are suitable for survival in form of assisted dispersal (Liu et al., 2014), assisted migration (Guinan et al., 2025) and assisted colonization (Gallagher et al., 2015). Ex situ conservation requires three criteria to be met: (i) Seed to seed, requiring relocated plants and animals to be able to grow freely and survive through sexual reproduction; (ii) Representation requires that relocated species maintain genetic integrity and represent the genetic diversity of the population; (iii) Maintaining the population gene frequencies of genes after translocation to avoid outbreeding depression, genetic assimilation and intragression (Engelmann and Engels, 2002; Quinlan et al., 2025). Targets 12 and 13 of the Aichi Biodiversity Targets call for the conservation of biological genetic diversity through ex situ conservation projects (Geijzendorffer et al., 2017), and countries around the world are actively exploring ex situ conservation systems, which have been extended to cover wildlife, crops, domesticated animals and microbial strains.

While significant achievements have been made in ex situ conservation, it is crucial to recognize its distinctive characteristics. (i) Unlike climate change refugia that emphasize population relocation and long-term retention in natural systems, ex situ conservation focuses on species under human intervention. For example, wild plant conservation primarily utilizes botanical gardens and seed banks; food and agricultural plant preservation employs germplasm repositories and nurseries; wild animal conservation relies on zoos, safari parks, aquaria, and other captive breeding programs; while microbial conservation is accomplished through strain conservation (FAO, 2007). (ii) Ex situ conservation

attempts may fail and even accelerate species extinction. A tragic example is the 1981 capture and captive breeding of Japan's last five crested ibises (*Nipponia nippon*), which ultimately failed to prevent the species' extinction in 2003 (Biodiversity Center of Japan, 2024). (iii) Under climate change scenarios, ecosystem transformations may become so profound that species reintroduction becomes unfeasible, potentially turning ex situ conserved populations into evolutionary relicts (Minteer, 2014). (iv) Technical constraints include: (a) climate model uncertainty and error may cause mis-translocation risk, as evidenced by the Poweshiek skipperling (*Oarisma poweshiek*) conservation program in the U. S., where climate model biases led to dramatic post-release survival declines (Runquist et al., 2025); (b) small population sampling reduces genetic diversity (Mclachlan et al., 2007). A global meta-analysis confirmed that inadequate wild population sampling resulted in significantly lower genetic diversity in restored populations compared to reference groups over 50 years, impairing long-term adaptive capacity (Wei et al., 2023); (c) microhabitat mismatches increase post-release mortality; and (d) translocated individuals can introduce or encounter novel pathogens. In Canada, the ex situ conservation of whitebark pine (*Pinus albicaulis*) faced dual threats: the absence of Clark's nutcracker (*Nucifraga columbiana*), its natural seed disperser in native habitats, and the concurrent spread of white pine blister rust (*Cronartium ribicola*) to recipient sites (Sáenz-Romero et al., 2021).

5.2 Monitoring invasive alien species

Climate change is a pivotal factor in the acceleration of invasive species incursions (Liu et al., 2017). Throughout the sequential process of biological invasions, the repercussions of climate change can emerge at various stages. To begin with, the warming climate may expedite the developmental pace and amplify the reproductive cycles of invasive species. Following this, climate change has the potential to reshape the distribution and the spatial extent of an organism's impact. Ultimately, the warming trend could augment the phenological flexibility, competitive prowess among species, and the growth-defense trade-offs of invasive flora, thereby disrupting the intricate relationships between hosts, pests, and predators (Gu et al., 2023). The encroachment of alien species, further perturbs biogeographical distributions, impinges on the diversity and genetic integrity of native species, and escalates the peril of extinction for indigenous taxa. It is estimated that invasive alien species and their management cost the global economy billions of dollars annually (IUCN, 2018). The Strategic Plan for Biodiversity (2011–2020) requires Parties to take urgent action to identify and prioritize invasive alien species pathways to prevent their introduction and rooting (CBD, 2015). To achieve these goals, the following aspects must be taken into account:

(a) Border controls are the first barrier. Biosecurity mechanisms must be established at the national level to regulate intentional introductions, use technology to mitigate the effects of unintentional introductions, and encourage community participation in monitoring and managing invasive alien species. Almost all countries have introduced regulatory provisions related to invasive alien species based on risk assessment, establishing strict quarantine controls at borders to prohibit the import and trade of regulated species; or using a white-listing approach to prohibit the introduction of all nonnative species unless they are determined to be low risk (Genovesi et al., 2015).

(b) Once invasive alien species have already invaded the region, eradication or impact mitigation must be pursued through conventional control, gene editing and other methods. Conventional control including physical control (Leary et al., 2013), chemical control (Simberloff et al., 2018) and biological control (Veitch et al., 2019). In the last decade, gene editing techniques have been progressively introduced, such as gene silencing, where specific genes of invasive species are not expressed or are not significantly expressed to reduce their spread (Martinez et al., 2020). Gene editing techniques are often used in combination with transgenesis and, while they can help to manage or eradicate of invasive alien species, their potential unintended consequences need to be addressed (Callaway, 2018).

(c) The involvement of stakeholders from across society is crucial for controlling invasive alien species. Widespread community participation can collect more valuable data on invasive alien species. For example, people can readily identify and record invasive alien species through mobile phones and apps, which not only further increases their awareness of biosecurity and early monitoring capabilities, but also helps to record their location and spread pathways.

6 Conclusions and future prospects

6.1 Conclusion

Compared to other anthropogenic environmental threats, climate change will exert more gradual, more difficult-to-quantify, and largely irreversible impacts on biodiversity. Given biodiversity's critical importance to human society and the inherent uncertainties of climate change, developing cross-scale adaptive management strategies is imperative. This paper examines adaptive management strategies to enhance biodiversity resilience under climate change, employing a cross-scale "region-landscape-site" framework. Key findings include:

(a) Cross-spatial-scale synergy is key to biodiversity adaptation to climate change. This study proposes that multi-scale collaboration across "regional–landscape–site" levels can systematically enhance the adaptive capacity of biodiversity to climate change and reduce its vulnerability. This finding deepens existing adaptation frameworks: whereas Mawdsley et al. (2009) focused on a horizontal classification of action types and Heller and Zavaleta (2009) emphasized the functional aspects of strategies, this study highlights the spatial dimension of vertical integration across scales, thereby extending the theoretical framework. This perspective aligns with insights from case studies such as those in the Andes (Hole et al., 2011) and coastal wetlands (He et al., 2025), which also identify cross-scale coordination as central to effective adaptation. This study further formulates a universal theoretical model, suggesting that scale synergy can address uncertainties associated with climate change through both "ecological cascading" and "governance implementation" dimensions. The primary contribution of this research lies in constructing a

systematic adaptation framework centered on "scale synergy," moving beyond earlier research paradigms that categorized actions or strategies in isolation. It reveals the inherent connections and interactive mechanisms among multi-scale conservation strategies. This systemic perspective can help policymakers identify scale disconnects during implementation and offers significant theoretical value for the adaptive management of complex ecosystems. However, the practical application of this framework faces several challenges, which also represent limitations of this study. These include scale mismatches between problem identification and governance levels, difficulties in identifying ecological cascades across spatial scales, barriers to vertical policy integration, and delays in adaptive management feedback.

(b) Biodiversity adaptation strategies at different scales have distinct emphases yet are mutually reinforcing. The regional scale focuses on top-down design and systematic assessment, providing strategic guidance for lower levels through macro-level planning and continuous monitoring. The landscape scale emphasizes spatial restructuring and network optimization—including protected area expansion, connectivity enhancement, and climate refuge identification—to facilitate species movement and persistence. The site scale prioritizes direct interventions targeting key species, such as *in situ*/ex situ conservation and invasive species control, representing the most immediate and concrete conservation actions. Although these strategies are widely recognized, the innovation of this study lies in integrating them into a coherent system with clearly defined hierarchical support relationships, elucidating the inter-dependencies among strategies across scales. For instance, species conservation at the site scale relies on landscape connectivity to support successful reintroduction and population recovery, while landscape optimization depends on regional-scale vulnerability assessments and planning prioritization. Together, these three scales form an organic whole: actions at lower levels facilitate the implementation of higher-level strategies, while upper-level planning provides the framework and basis for localized interventions. Nevertheless, integrating multi-scale strategies still faces resource- and knowledge-related barriers, such as: (i) competition for limited conservation funding among strategies operating at different scales, making optimal resource allocation challenging; and (ii) difficulties in effectively integrating site-level monitoring data into landscape and regional scales to support macro-decision-making, coupled with the generally insufficient resolution of regional climate models to provide precise guidance for site-specific management.

6.2 Future prospects

The adaptation of biodiversity to climate change is a long-term, social learning process that requires individuals and societies to increase their awareness of potential future changes and enhance their capacity to cope with them. Future efforts must address critical challenges, including social inequities, lags in dynamic landscape conservation planning, dynamic imbalances in species' ecological networks, and barriers to interdisciplinary support.

(a) At the regional scale, policies for biodiversity adaptation confront both domestic and international social inequities. Biodiversity conservation has significant positive externalities. However, biodiversity-rich regions are often less developed regions that face three constraints: development limitations imposed by conservation requirements. High dependence on climate-sensitive sectors (e.g., agriculture), and lack of technical and financial resources to withstand climate change (Marshall et al., 2016). Furthermore, climate change may exacerbate current regional inequalities (Feliciano et al., 2025). Therefore, future policy design and international cooperation must explicitly incorporate equity, fairness, and distributional considerations, evaluating how policies affect balanced regional development, stakeholders responses, and the burden placed on the poor, etc.

(b) At the landscape scale, response lags in dynamic landscape-conservation planning pose a future challenge. Natural disturbances, succession and climate cycles drive spatial shifts in suitable habitats. Dynamic landscape conservation explicitly addresses biodiversity's climate adaptation needs at this scale, incorporating both structural and functional connectivity responses to environmental change (Xu et al., 2025). By enhancing cross-scale, long-term monitoring, climate impact assessments, and risk analyses, this approach enables prediction of species redistribution and ecosystem transitions, quantification of landscape-level dynamics, and development of proactive conservation targets to guide adaptive management. Regrettably, a major constraint remains: the limited availability of large-scale, high-resolution, long-term ecological datasets essential for reliable implementation.

(c) At the site scale, dynamic imbalances in species' ecological networks hinder the maintenance of complex ecosystem stability, thereby impeding species adaptation. While flagship species such as the giant panda and Asian elephant attract policy attention and function as umbrella species, the neglect of non-charismatic or lower-trophic-level species can alter matrix ecosystem structure (Poiani et al., 2000), undermine network stability, and erode adaptive capacity. Ecological-network models require actions that explore the links between complexity and stability (Landi et al., 2018), and foster dynamic equilibrium within habitats, thereby promoting species adaptation and sustaining ecosystem services.

(d) Interdisciplinary support across all three scales remains inadequate. Most existing proposals focus on ecology disciplines, underestimating the contribution of the social sciences. Effective biodiversity adaptation across spatial scales demands large geographical coverage, long time-frames, integration with species-conservation plans, natural resource management, and the livelihoods of local people, etc. (Frison, 2024). Capacity building must therefore be truly multidisciplinary, engaging atmospheric sciences, biology, ecology, geography, agronomy, sociology, economics and management.

(e) It is imperative to heighten attention to the synergistic impacts of human activities and climate change on biodiversity. Climate change, human activities, and their interactions are the

strongest drivers of biodiversity loss. Although the scientific community has directed significant concern towards climate change (Mazor et al., 2018), it is crucial to acknowledge that human actions, especially those involving excessive development, continue to pose the most significant threat to species at risk as noted in the IUCN Red List (Maxwell et al., 2016). Habitats conversion driven by agricultural expansion, deforestation, marine fishing, and urban sprawl—exacerbated by climate change—constitutes the primary cause of biodiversity decline. The cumulative amplification of multiple stressors can trigger cascading effects, potentially undermining conservation initiatives (Brook et al., 2008). Future research endeavors should concentrate on elucidating the intricate interplay between climate change and human activities in relation to biodiversity, and devising integrated planning and management strategies.

Author contributions

XM: Writing – review & editing, Writing – original draft, Funding acquisition, Conceptualization, Visualization, Methodology. LJ: Investigation, Methodology, Writing – original draft. LS: Writing – original draft. ZQ: Project administration, Writing – review & editing, Funding acquisition, Supervision.

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Who speaks for climate migrants? A justice-oriented bibliometric analysis of Global South research

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This study presents a comprehensive bibliometric analysis of climate-induced migration research in the Global South (2000–2024), critically examined through the lens of climate justice. Drawing on 204 peer-reviewed publications from Scopus and Web of Science, the analysis maps scholarly production, citation patterns, thematic evolution, and global collaboration networks using Biblioshiny and VOSviewer. Results reveal a significant surge in research post-2015, with intellectual roots grounded in environmental migration, but shifting progressively toward integrated themes of climate justice, human rights, adaptation, and vulnerability. High-impact contributions remain concentrated among Global North institutions, particularly the United States, United Kingdom, and Australia, although authorships are increasingly diversifying to include regions such as South Asia, Sub-Saharan Africa, and Small Island Developing States. Thematic mapping shows a maturing field marked by convergence of legal, political, ecological, and social science perspectives. However, critical gaps persist including limited attention to under-researched geographies, destination outcomes, gendered and intersectional experiences, and understanding trapped populations and immobility. South–South collaborations remain marginal, and dominant framings often reproduce epistemic hierarchies that overlook local agency and decolonial critiques. The study identifies urgent directions for future research, including deeper interdisciplinary integration, participatory and context-sensitive methodologies, and the application of attribution science to quantify climate-related displacement. By centering equity, representation, and the differentiated impacts of climate stress, this bibliometric perspective contributes not only to mapping the landscape of climate migration scholarship but also to advancing a justice-oriented research agenda. It calls for a paradigm shift where migration is understood not merely as a risk, but as a space for resilience, rights, and transformation, particularly for the most vulnerable in the Global South.

KEYWORDS

climate-induced migration, Global South, climate justice, bibliometric analysis, epistemic justice, vulnerability and equity

Introduction

The core objective of this paper is to systematically examine how research on climate-induced migration in the Global South has evolved, particularly through a climate justice lens. We aim to identify knowledge gaps, thematic trends, and structural imbalances in authorship and collaboration, offering insights into the extent to which existing literature addresses issues of vulnerability, equity, and representation. To this end, we employ a bibliometric approach to

assess intellectual structures, co-authorship networks, citation patterns, and thematic clusters in the field. This framing ensures that our analysis remains explicitly guided by questions of justice, knowledge asymmetries, and the lived realities of climate-vulnerable populations.

Foregrounding this aim is vital because climate-induced migration has become one of the most pressing consequences of the climate crisis. Worsening hazards, from extreme heat and drought to floods and sea-level rise, are uprooting livelihoods and forcing people to move in ever-growing numbers (Almulhim et al., 2024). In 2020 alone, over 30 million people were displaced by climate-related disasters, with Asia and the Pacific among the hardest-hit regions (IFRC, 2021). By 2050, climate impacts could internally displace about 143 million people in the Global South, including ~86 million in Sub-Saharan Africa, 40 million in South Asia, and 17 million in Latin America (Baldwin, 2017; Barrios et al., 2006). These projections confirm that climate-induced migration is not a distant scenario but an unfolding reality threatening lives, stability, and development across vulnerable regions.

A climate justice perspective highlights why this subject demands urgent scholarly and policy attention. Those most vulnerable to climate change, often low-income communities in the Global South, have contributed least to the greenhouse gas emissions that drive it (Arruda Filho et al., 2024). For example, Africa produces only a fraction of global emissions yet faces some of the most severe impacts. Climate justice reframes migration not simply as an environmental or humanitarian challenge but as a matter of fairness, ethics, and human rights. It emphasizes the responsibility of major polluters and the international community to support those forced to move, through adaptation assistance, legal recognition of climate-displaced persons, and mechanisms like loss-and-damage compensation. This aligns with global policy frameworks such as Sustainable Development Goal 10, which calls for safe and responsible migration, a target jeopardized by unchecked climate extremes.

Defining climate-induced migration

"Climate-induced migration" refers to human mobility triggered primarily by climate change and related environmental hazards. It encompasses sudden displacement (e.g., fleeing floods or cyclones), planned relocation, and gradual out-migration from areas rendered uninhabitable by slow-onset changes such as drought or sea-level rise. Climate is rarely the sole cause; rather, it interacts with economic, social, and political drivers (Priovashini and Mallick, 2022). Black et al. (2013) highlight that environmental stress is one among many factors shaping migration decisions.

Scholarship increasingly rejects simplistic "climate refugee" narratives and instead distinguishes between voluntary migration, forced displacement, and immobility or "trapped" populations. Migration may be proactive, such as seasonal rural-to-urban movements, whereas displacement implies limited choice, and immobility reflects households unable to move due to poverty or legal barriers. These distinctions recognize both vulnerability and agency, highlighting migration as a potential form of adaptation if supported through policy and resources. Indeed, frameworks such as *migration as adaptation* suggest that planned, facilitated mobility can be a strategy for adjusting to climate stress rather than a failure of coping (Black et al., 2013).

Critical scholarship also warns against securitized framings that portray climate migrants as threats (McLeman, 2018). Such perspectives risk reinforcing border control rather than protection. Instead, a human security approach emphasizes dignity, safety, and agency. Overall, climate-induced migration is best understood as part of a continuum of mobility shaped by complex socio-political contexts.

Climate justice and migration

Climate justice is rooted in the principle that those least responsible for climate change often face its gravest consequences. It demands equitable sharing of burdens and responsibilities (Arruda Filho et al., 2024). Within migration scholarship, justice has distributive, procedural, recognition, and reparative dimensions. Distributive justice calls for fair allocation of adaptation resources and loss-and-damage compensation; procedural justice emphasizes inclusive decision-making in relocation; recognition justice stresses valuing marginalized knowledge and voices; and reparative justice addresses historical responsibilities for displacement.

At the global scale, climate justice highlights the North–South paradox: wealthy nations have historically emitted the bulk of greenhouse gases, while poorer countries bear disproportionate vulnerability (Roberts and Parks, 2006; Sultana, 2022). Small island states and least-developed countries contribute little to emissions yet face existential risks from rising seas and storms. This confers moral obligations on high-emitting countries to finance adaptation, reduce emissions, and support displaced communities.

Climate justice also operates at national and local levels, where marginalized groups within societies are hardest hit and least able to adapt. The IPCC (2022) acknowledges that "ongoing impacts of colonization" undermine adaptive capacity, linking historical injustices to present vulnerabilities (Morrison et al., 2023). In contexts such as the Pacific Islands, postcolonial critiques explicitly connect legacies of marginalization with heightened climate risks.

Applied to migration, a justice lens shifts the focus beyond numbers of displaced persons to questions of rights, responsibilities, and agency. It asks whether climate migrants are protected under international law (they currently lack a formal legal category), whether communities participate in relocation decisions, and whether adaptation funds reach those most vulnerable. This framing critiques Global North securitization discourses that prioritize border protection, contrasting them with Global South calls for mobility support and equitable adaptation.

Epistemic justice is equally critical. Bibliometric asymmetries—including Global North–dominated authorship and limited South–South collaboration—influence which diagnoses and remedies are considered legitimate (Parsons et al., 2024). Unless countered by co-production, inclusive citation practices, and Southern institutional empowerment, research risks reproducing colonial hierarchies of knowledge (Sultana, 2022).

Rationale and contribution

Against this backdrop, our study is motivated by the need to systematically evaluate the state of research on climate-induced

migration in the Global South through a bibliometric lens. While the concept has gained traction in academic and policy circles, research output remains skewed toward Global North institutions, often marginalizing Southern voices and priorities (Chakrabarti, 2023). This imbalance obscures the lived realities of climate-vulnerable populations in the Global South and risks reinforcing inequitable policy agendas.

A bibliometric approach enables a rigorous, transparent, and replicable mapping of the field. It allows us to identify thematic clusters, collaboration networks, and citation patterns while assessing whether the literature incorporates principles of climate justice. Specifically, our analysis traces how migration is framed, who produces knowledge, and how Southern research is positioned in global discourse (Arruda Filho et al., 2024; Anjum and Aziz, 2025a; Donthu et al., 2021).

Research questions

This paper is guided by three interrelated questions:

1 How has the academic literature on climate-induced migration in the Global South evolved over time, and what thematic trends can be identified?
2 What structural imbalances exist in terms of authorship, collaboration, and knowledge production, particularly between Global North and Global South institutions?
3 To what extent does the literature engage with principles of climate justice—distributive, procedural, recognition, and reparative, in framing migration?

By systematically addressing these questions, this study contributes to efforts to decolonize climate research and foreground justice in the study of climate-induced migration.

Materials and methods

Bibliometric analysis has been fundamental in mapping key themes, citation networks, and interdisciplinary collaborations (Kumar, 2025). Though bibliometric analysis is widely recognized and a powerful research tool that quantitatively analyzes academic literature, its application in the climate migration domain is limited. Nonetheless, bibliometric analysis is essential for evaluating research landscapes, gaps and driving trends (Saeid et al., 2025), emerging areas (Donthu et al., 2021), and research hubs (Carrascal-Hernández et al., 2025), including in the context of climate justice (Anjum and Aziz, 2025a).

Since bibliometric analysis follows a systematic and structured approach (Passas, 2024), this study adheres to established research protocols to ensure rigor and reproducibility. The combination of Scopus and Web of Science (WoS) datasets is used in the data analysis. Both are widely used datasets in bibliometric analysis due to their comprehensive, rigorous quality, indexing of peer-reviewed literature, citation tracking capabilities, and analytical tools (Arsova et al., 2022; Kumpulainen and Seppänen, 2022). While WoS dataset is based on selectivity, Scopus offers comprehensive data. The integration of both enhances the reliability of bibliometric studies, and our study integrates both datasets.

Data analysis and visualization

WoS and Scopus have different index coverages, and they store information differently, which leads to potential biases (Kumpulainen and Seppänen, 2022) inconsistencies while merging. Consequently, researchers employ different methodological approaches to counter missing data and duplicate records. For data analysis, researchers have used the open source Bibliometric package of R (Biblioshiny) (Wei and Jiang, 2023), VOSviewer (Kirby, 2023), CiteSpace (Zhang et al., 2023), SciMAT (Cobo et al., 2012), ScientoPy (Ruiz-Rosero et al., 2019). However, most of these software requires professional skills and specialized expertise to operate effectively. To address this, recently, (Caputo and Kargina, 2022) presented a user-friendly method to merge Scopus and WoS data with the R package in Biblioshiny. We follow the guide provided by Caputo and Kargina (2022) for merging the datasets in Biblioshiny.

Biblioshiny is a web-based visual analysis tool built on the Bibliometrix package in R Studio, which is designed for bibliometric data processing and analysis. We employed Biblioshiny 2.0 for data analysis (Aria and Cuccurullo, 2017) and VOSviewer for visualization to map co-citation networks, keyword occurrence, and citation analysis of countries.

Operational definition of Global South: In this study we conceptualize the *Global South* primarily as a politico-economic and epistemic category denoting states historically positioned at the periphery of global power and knowledge production, rather than a strictly geographic bloc. Consistent with UN usage and contemporary scholarship, we operationalize the Global South as G77 + China (134 states) for search and inclusion purposes, aligning our queries to the House of Commons Library country list used in the data extraction (Annex 1). This approach recognizes substantial internal heterogeneity (e.g., lower-income small island states vs. large emerging economies) and guards against essentialism by treating the Global South as a relational construct whose boundaries and coalitions shift across policy arenas and scholarly fields (Bull and Banik, 2025; Mazzega et al., 2025). We therefore interpret bibliometric patterns with caution, emphasizing how geopolitical position and epistemic hierarchies shape visibility, authorship, and citation dynamics.

Eligibility criteria and screening

A list of 134 Global South countries was obtained from House of Commons Library to guide the data extraction process. The following criteria keywords, "climate migration*" OR "environmental migration*" OR "climate-induced migration*" OR "climate displacement*" OR "environmental displacement*" OR "climate refugee*" were combined with the list of the Global South countries to retrieve the scientific data on climate-induced migration from 2000 to 2024 (see Annex 1). The variation among keywords was maintained by using asterisk (*) after each keyword. For instance, "climate migration*" results in "climate migration" and "climate migrations" (WoS Help, 2020). The search was conducted on March 05, 2025.

Although the search was designed to focus on climate-induced migration in the Global South; however, the results include documents from both the Global North and the Global South institutions. It is due to the global significance of climate migration, the role of international research collaborations, and the fact that researchers in the Global North contribute to policy frameworks, legal debates, and destination analyses. Lastly, the indexing bias of bibliographic databases contributes to the visibility of research from well-established academic institutions, regardless of study location (Table 1).

After defining the search keywords, a query was formulated and fed into WoS, and it returned 228 documents. Following document type and language filters, only articles and review articles published in English were retained, as they undergo rigorous quality control processes (Milán-García et al., 2021). In the end, a BibTeX file with 188 documents was downloaded. For Scopus, the initial search yielded 380 documents. After applying similar filters, 239 articles were downloaded in BibTeX format.

The WoS (BibTeX) and Scopus (BibTeX) files were uploaded to Biblioshiny as raw datasets, from which Excel files (WOS.xlsx and Scopus.xlsx) were extracted. These files were manually merged within Excel, and 163 duplicate records were removed. The resulting dataset of 264 articles was subjected to further manual screening (Figure 1).

A thorough revision was conducted to remove any irrelevant articles, leading to the removal of 60 documents. These articles appeared in the list as they used some keywords but were not directly relevant to climate-induced migration. In the end, an Excel file with 204 documents was fed into Biblioshiny, for analysis and a ".csv" file for VOSviewer to facilitate network visualization.

We include all peer-reviewed studies that focus on climate-induced migration in Global South regions, regardless of the author's institutional affiliation. This allows us to analyze who is producing knowledge on Global South contexts, what the dominant themes are, and how climate justice framings are integrated.

We screened both titles and abstracts to determine relevance. Only English-language peer-reviewed articles and reviews were included, which introduces a language bias. Moreover, our keyword strategy may have excluded papers that do not explicitly use terms like 'climate migration' or omit country names in titles/abstracts. We acknowledge that key literature on immobility, stepwise migration, and internal displacements may be underrepresented due to these constraints. We reflect on these limitations in our discussion.

Our dataset consists of 204 documents that come from 152 sources and include 659 authors. The annual growth rate of publication was 20.25%. Notably, only 42 documents were authored by a single researcher which indicates a strong trend toward collaborative research. The dataset includes 634 author keywords which encapsulate a wide range of topics within climate-induced migration. The earliest publication in the dataset dates back to 2004, and 40 articles were published in 2024. Although the publication frequency remained relatively gradual until 2012, a substantial growth has been observed since 2017.

While our initial search strategy prioritized migration-related terms combined with Global South country names, we intentionally did not restrict the search to include justice-related keywords. This decision was made to avoid excluding migration studies that engage with justice implicitly, through themes of vulnerability, adaptation, gender, or human rights, even if "justice" was not an explicit keyword. Importantly, our bibliometric analysis revealed that justice-related concepts emerged strongly in the dataset itself, as seen in the co-occurrence clusters (Figure 2; Table 2) where *climate justice*, *human rights*, and *gender* featured prominently. This confirms that the justice–migration nexus is empirically represented in the literature we analyzed, even without front-loading justice terms in the search query.

Author keywords provide a structured way to identify research patterns, thematic evolution, and the intellectual structure of a field in bibliometric analysis. Keywords are also useful in indexing and categorizing research and conveying the topics of articles (Pearson, 2024). Figure 2 shows the co-occurrence of author keywords from 2000 to 2024 for 204 documents. For 682 keywords, minimum occurrence criteria were set to 5 and 22 keywords met the threshold. In result we get the mostly used author keywords in climate-induced migration research. Authors' keywords are grouped into four main clusters. The color of the clusters reflects the strength of relationships among keywords, while the size of the nodes represents how frequently a keyword appears. The lines between nodes indicate connections between them. Figure 2 shows the co-occurrence of author keywords from 2000 to 2024 across 204 documents. The network reveals four distinct clusters: (1) climate change, adaptation, vulnerability, and livelihoods; (2) climate justice, human rights, gender, and refugees; (3) displacement, environmental migration, and India; and (4) climate-induced migration and regional foci such as Bangladesh and Sub-Saharan Africa. Notably, the presence of *climate justice*, *human rights*, and *gender* as central nodes confirms that justice-oriented perspectives are empirically embedded in the literature, even though our search terms did not pre-filter for "justice." This validates the study's focus on the nexus of climate justice and climate-induced migration, demonstrating how normative, rights-based, and

TABLE 1 Summary of results.

Description	Results
Timespan	2004:2024
Sources (Journals, Books, etc.)	152
Documents	204
Annual Growth Rate %	20.25
Document Average Age	4.9
Average citations per doc	11.37
References	11,023
Document contents	
Keywords Plus (ID)	483
Author's Keywords (DE)	634
Authors	
Authors	659
Authors of single-authored docs	39
Authors collaboration	
Single-authored docs	42
Co-Authors per Doc	3.41
International co-authorships %	38.24
Document types	
Article and Review Article	204

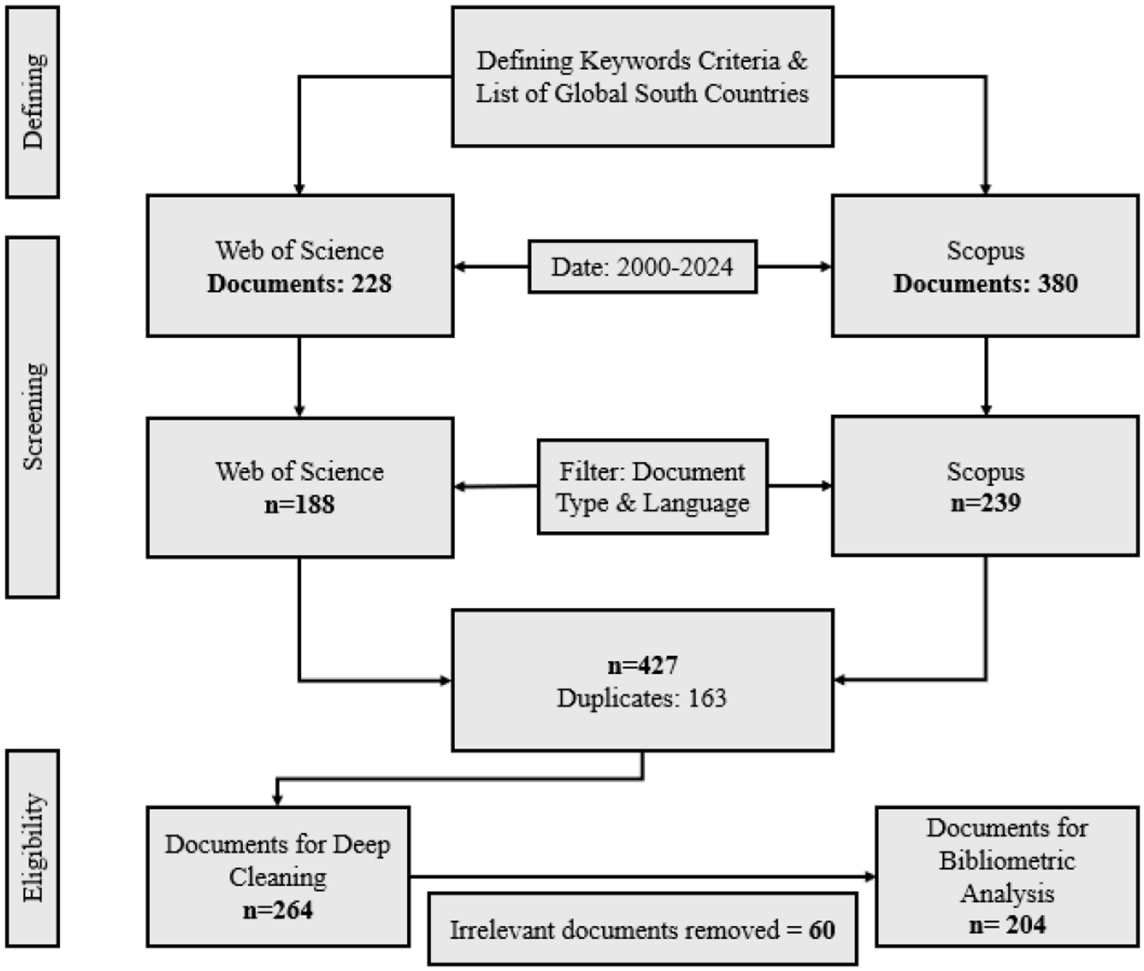


FIGURE 1
PRISMA flow diagram.

equity-focused framings have increasingly shaped the intellectual structure of the field since 2015.

Figure 3 illustrates the average number of citations per document from 2004 to 2024. Citations increased steadily after 2012 and reached a peak around 2018. However, this was followed by a gradual decline, as indicated by the downward trend. This also shows that newer publications have yet to accumulate citations. During the peak in 2018, there were 4.70 total citations, which has reduced to 0.48 in 2024. The post-2018 decline reflects citation lag rather than waning interest; importantly, it also flags enduring citation inequities, newer Global South scholarship published since 2020 has had less time and fewer channels to accrue recognition, a phenomenon central to epistemic justice debates." (cf. Donthu et al., 2021; see also our discussion of asymmetries).

Figure 4 enlists the top 10 most productive authors who have contributed to the research on climate-induced migration. The bigger node indicates the publication volume. Mallick Bishawjit and Mayer, Benoit have bigger nodes. However, Mayer, Benoit was the most productive author in 2013, but newer authors have become more active. While Byravan Sujatha and Bezu Sosina, have maintained their publication flow research over multiple years. Overall research output has increased over time, particularly in post-2019, indicating a growing field.

Table 3 presents the publications by top affiliations. In the top 10 relevant affiliations, Hohai University ranks 1st with 8 articles, followed by Caldas University and University of Galway with 7 articles each. Makerere University remains in 10th position with the contribution of five articles. Institutions from both the Global South and North are found to be equally engaged in climate migration research. The first publication from Hohai University was registered in 2022, and by 2023 it had published a total of eight articles. Notably, the activity around climate migration has intensified after 2018.

Figure 5 shows the number of articles published by corresponding authors from different countries. MCP refers to Multiple Country Publications and SCP refers to Single Country Publications. The highest number of corresponding authors is recorded from India and China. Authors from India, China, Bangladesh mostly published as single country publications, whereas the USA, UK, and Germany have a higher proportion of multi-country collaborative research. Notably, all corresponding authors from Brazil have published exclusively through SCP, whereas those from Australia have contributed solely to MCP publications. Interestingly, authors from Global North countries are more involved in international collaborations compared to authors from the Global South.

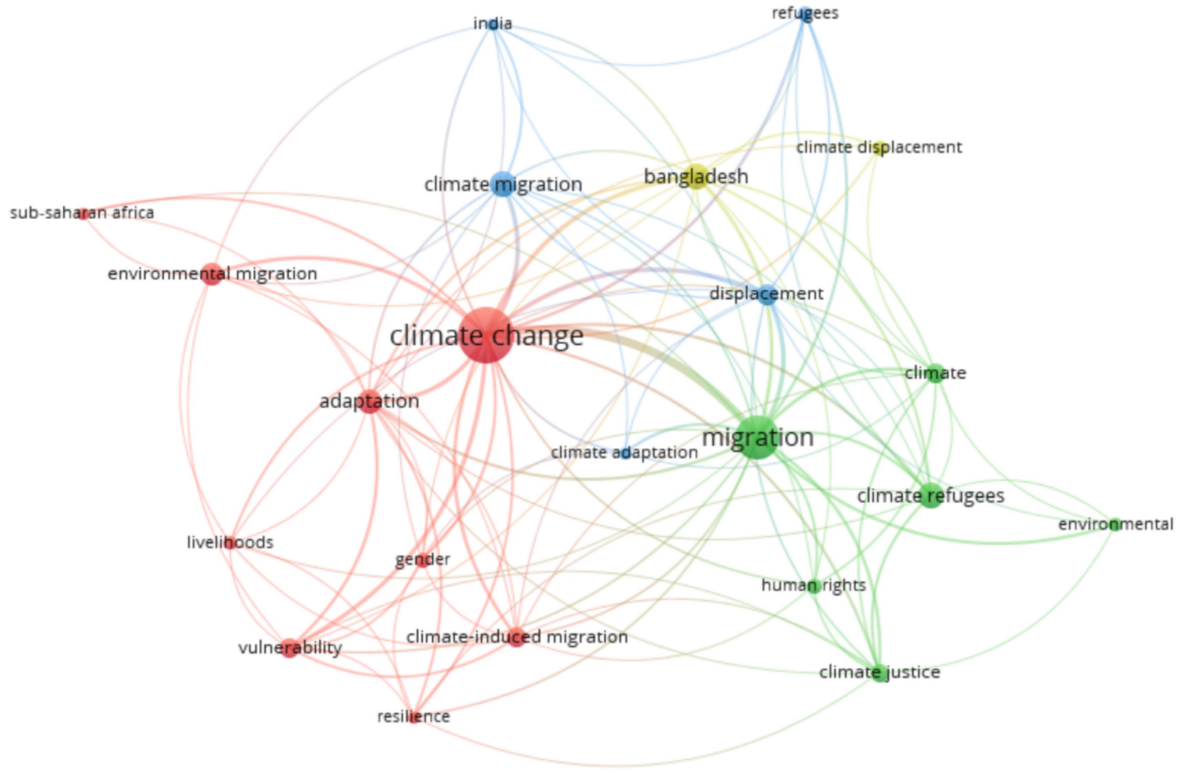


FIGURE 2
Network analysis of author keywords.

TABLE 2 Keywords clusters.

Cluster 1 (red)	Cluster 2 (green)	Cluster 3 (blue)	Cluster 4 (yellow)
Adaptation	Climate	Climate adaptation	Bangladesh
Climate change	Climate justice	Climate migration	Climate displacement
Climate-induced migration	Climate refugees	Displacement	
Environmental migration	Environmental	India	
Gender	Human rights	Refugees	
Livelihoods	Migration		
Resilience			
Sub-Saharan Africa			
Vulnerability			

Scientific research on climate migration is particularly widespread in Asia, North America, and some parts of Europe. Figure 6 shows the countries' scientific production. China is leading in the scientific production with 70 articles, followed by the USA (57) and India (54). Similarly, Bangladesh and the United Kingdom are also important contributors with 44 and 32 documents, respectively. A significant increase in scientific production has been witnessed, especially in China, India, and the United States. By 2024, India reached 54 articles, and Bangladesh had 44. The USA and the UK began publishing actively around 2014, with substantial increases in recent years.

If we compare the total citations, the United States significantly leads with 451 citations. However, China and India have 291 and 256 citations. United States (37.6) also leads in average citations per article followed by the United Kingdom (26), Poland (25), Bahamas (21) and Pakistan (20). However, China (17.1) and India (10.7) with a large number of publications have lower average citations.

Citation analysis at the country level is a fundamental aspect of bibliometric analysis as it evaluates citation patterns across countries. Figure 7 visually represents the citation analysis of countries. Among 237 countries, 23 met the threshold of at least five citations in our dataset. In this network, the size of each node corresponds to the citation weight of the country, while the lines between nodes indicate citation connections. The label size reflects the relative importance of each country, based on PageRank values. Countries such as the USA, Germany, UK, and Australia have received the highest number of citations. USA, India, and China emerge as key contributors with

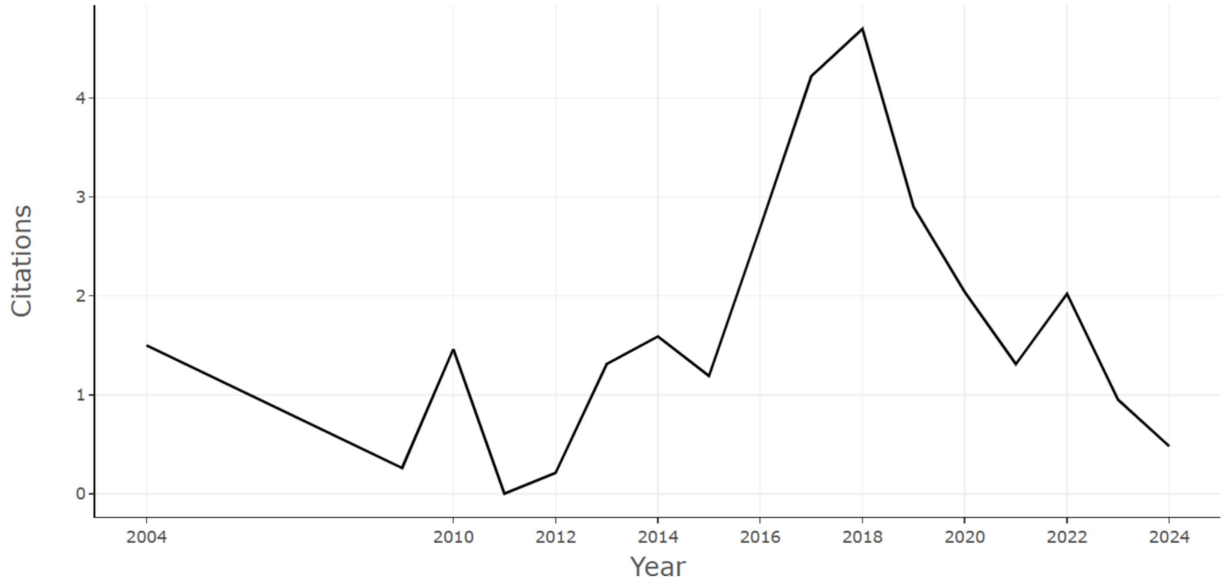


FIGURE 3
Average citation per year.

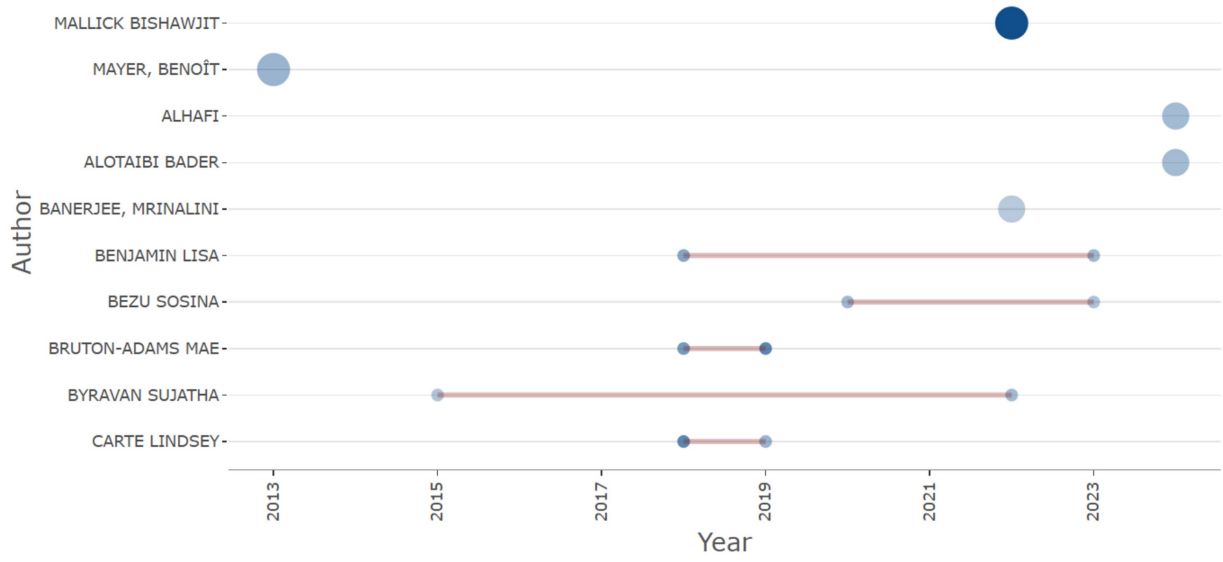


FIGURE 4
Most relevant authors and their production over time.

strong citation connections, indicating their central role in shaping the discourse (Figure 8).

Table 4 indicates the most highly cited documents on climate-induced migration, published from 2000 to 2024. The article "Climate Variability and International Migration: The Importance of the Agricultural Linkage," written by Ruohong Cai and published in the Journal of Environmental Economics and Management, has accumulated 177 citations and stands highest in our dataset. This article finds a strong linkage between temperature and cross-country migration in agriculture-dependent countries. The most recent article with the least citations was titled "Environmental Migration Effects of Air Pollution: Micro-Level Evidence from China." It was written by Qingbin and published in Environmental Pollution. This article finds that air pollution increases the probability of internal migration. Altogether, these articles have been cited 768 times.

Table 5 shows the most productive journals in our dataset. These journals have 39 publications and 726 citations. Three of the articles were published by Springer and two by Taylor & Francis. The h-index is a widely used metric for measuring academic impact by assessing both publications and their citations, while the g-index ensures that the top "g" papers have received at least "g^2" cumulative citations. Despite criticism, the h-index remains a key indicator of a researcher's scientific production (Formoso, 2022).

TABLE 3 Distribution by affiliations.

Affiliation	Articles
Hohai University	8
Caldas University	7
University of Galway	7
China Agricultural University	6
Mahidol University	6
Shahjalal University of Science and Technology	6
International Center for Tropical Agriculture (CIAT)	5
Macquarie University	5
Makerere University	5

The journal 'Climatic Change' has the highest number of publications (7) with citations (104). However, 'International Journal of Climate Change Strategies and Management' has five publications but 202 citations. 'Strategies and Management' is the third most influential journal with five publications and 60 citations. The journal 'Climatic Change' also leads in h-index (4) and g-index (7).

Climate change is found to be the most dominant keyword in our dataset which appeared 87 times. After that migration occurred 56 times and climate migration accrued 19 times. The use of other terms such climate refugees, environmental migration, displacement, adaptation, vulnerability and climate justice indicates that discussion is not limited to just migration but also the coping mechanisms, risks, and resilience and aftermaths. The use of these keywords increased

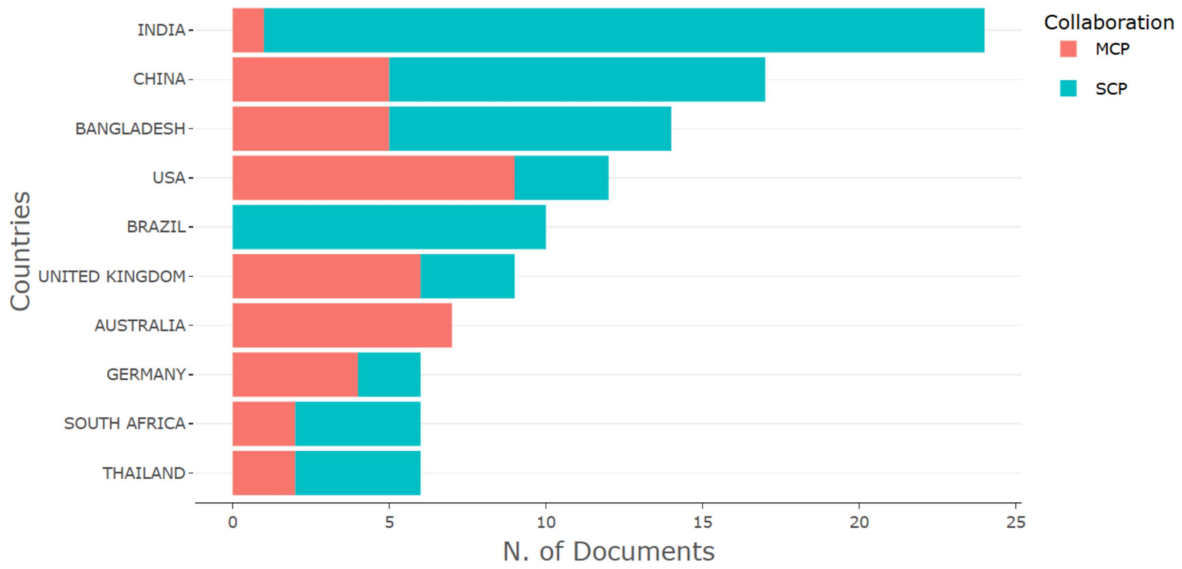


FIGURE 5
Distribution by author's corresponding countries.

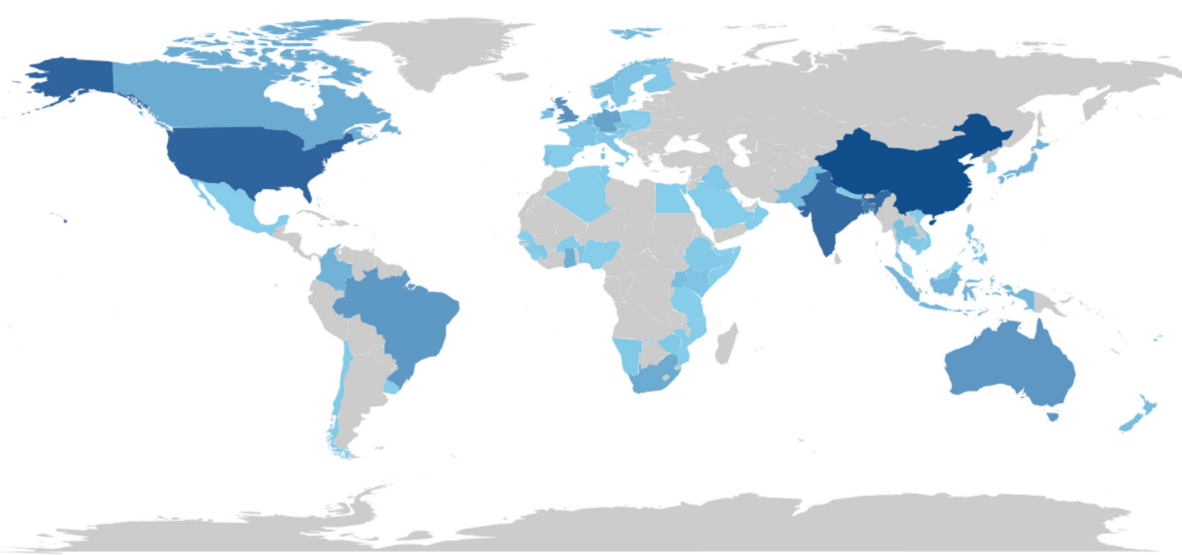


FIGURE 6
Countries' scientific production.

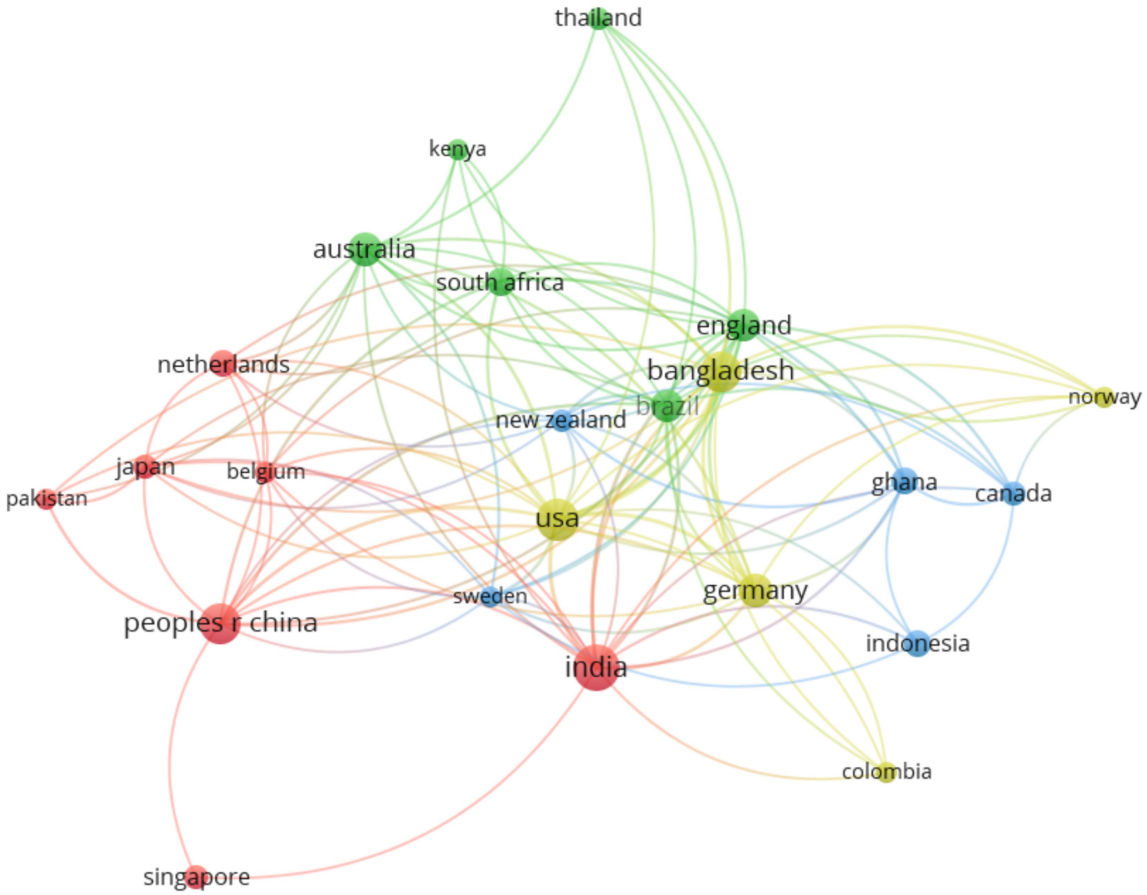


FIGURE 7
Citation analysis of countries.

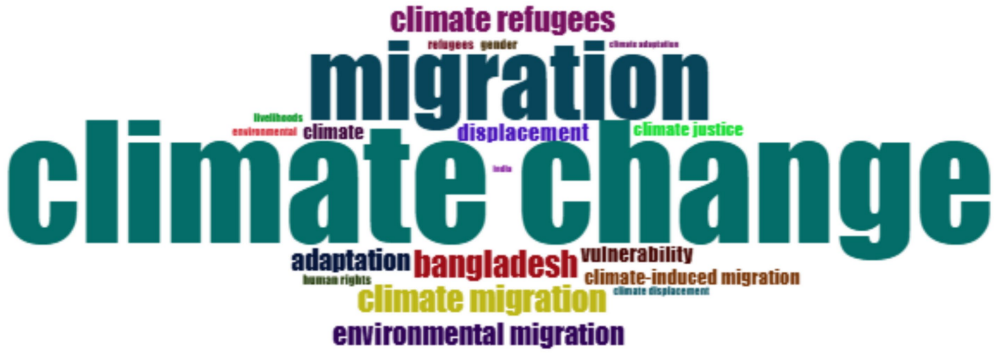


FIGURE 8
World cloud of author's keywords.

drastically after 2018. Interestingly, keyword 'Bangladesh' occurred 19 times, which shows its significance as a key study area in climate migration.

Figure 9 shows the temporal evolution of key topics in climate migration research, based on author keywords. Horizontal lines indicate years during which a specific term has been actively used in the literature, while the bubble size represents the frequency of occurrence. Environmental migration and climate refugees were among the earliest used terms to appear in research. The last few years have seen a surge in terms such as climate migration, displacement, and human rights. Much of the focus is being placed on the legal and social dimensions of climate-induced migration. Newer themes such as resilience, gender, adaptations and human rights are gaining greater attention.

Figure 10 visualizes global collaboration among researchers. The United States has emerged as a hub of collaboration with the highest

TABLE 4 The 10 most highly cited documents.

Documents	Reference	Year	TC	TC per Year
Climate variability and international migration: The importance of the agricultural linkage	Cai et al. (2016)	2016	177	17.70
Migration as adaptation strategy to cope with climate change: A study of farmers' migration in rural India	Jha et al. (2018)	2017	115	14.38
Climate change and forced migrations: An effort towards recognizing climate refugees	Berchin et al. (2017)	2017	96	10.67
Toward a Political Ecology of Migration: Land, Labor Migration, and Climate Change in Northwestern Nicaragua	Radel et al. (2018)	2018	66	8.25
One step forward, two steps back? The fading contours of (in)justice in competing discourses on climate migration	Bettini et al. (2017)	2016	63	7.00
Lessons From the Pacific Islands – Adapting to Climate Change by Supporting Social and Ecological Resilience	Mcleod et al. (2019)	2019	58	8.29
Linking climate-induced migration and security within the EU: insights from the securitization debate	Trombetta (2014)	2013	53	4.42
Raising the voices of Pacific Island women to inform climate adaptation policies	Mcleod et al. (2018)	2018	48	6.00
Social impacts of the climatic shift around the turn of the 19th century on the North China Plain	Fang et al. (2013)	2012	46	3.54
Environmental migration effects of air pollution: Micro-level evidence from China	Guo et al. (2022)	2022	46	11.50

TABLE 5 Distribution by influential journals.

Source	H_Index	G_Index	Publisher	TC*	NP**	FPY***
Climatic Change	4	7	Springer	104	7	2014
International Journal of Climate Change Strategies and Management	4	5	Emerald	202	5	2017
Climate And Development	3	5	Taylor & Francis	60	5	2014
Geographical Journal	3	3	Wiley	78	3	2017
International Journal of Disaster Risk Reduction	3	3	Elsevier	22	3	2018
Regional Environmental Change	3	3	Springer	72	3	2014
Sustainability	3	6	MDPI	87	6	2017
Ambio	2	2	Springer	55	2	2022
Asian Population Studies	2	2	Taylor & Francis	21	2	2012
Economic And Political Weekly	2	3	Sameeksha Trust	25	3	2009

*Total citations, **Number of publications, ***First publication year.

number of international collaborations with China, Bangladesh, the UK, India, and Australia. Apart from the United States, climate migration research is dominated by China, India, and Australia. Meanwhile, European countries, particularly the UK and Germany, serve as secondary hubs, forming strong links with both Global North and Global South institutions. However, South–South collaborations remain limited, with most partnerships occurring through Global North institutions. The network structure makes visible the North-led brokerage and thin South–South ties, implying that evidence and frames travel along unequal corridors of influence—*a justice issue in its own right* that shapes which adaptation/mobility solutions gain traction.

Figure 11 shows the thematic map based on author keywords. The Thematic Map is suitable to understand the relevant issues (Bagdi et al., 2023) by understanding the present status and analyzing the future direction in the field (García-Lillo et al., 2023). The map categorizes research themes based on development (density) and relevance (centrality) within climate migration literature and divides into four quadrants. This thematic map was generated using a clustering technique (Louvain) algorithm where research themes were grouped based on their relevance and development. Thematic centrality of 'adaptation', 'livelihoods', and 'vulnerability' signals the field's shift from crisis talk to justice-attentive, agency-recognizing framings; yet the Basic/Transversal quadrant shows that key justice concepts remain under-integrated, underscoring the need for South-led theorization.

Motor Themes located on the upper right quadrant are well-developed and highly relevant, central, and dense themes. Keywords such as climate change migration, adaptation, vulnerability, and environmental migration with livelihoods. These themes advance discourse and reflect core policy and resilience strategies.

The upper left Quadrant indicates themes that are well-developed, specialized and dense, but less central to the overall discourse. Topic areas such as ecosystem services and international migration fall here. These peripheral themes are important yet not widely interconnected with other major themes.

The Bottom Right Quadrant is based on themes which have high relevance but are less developed networks. Adaptation, vulnerability,

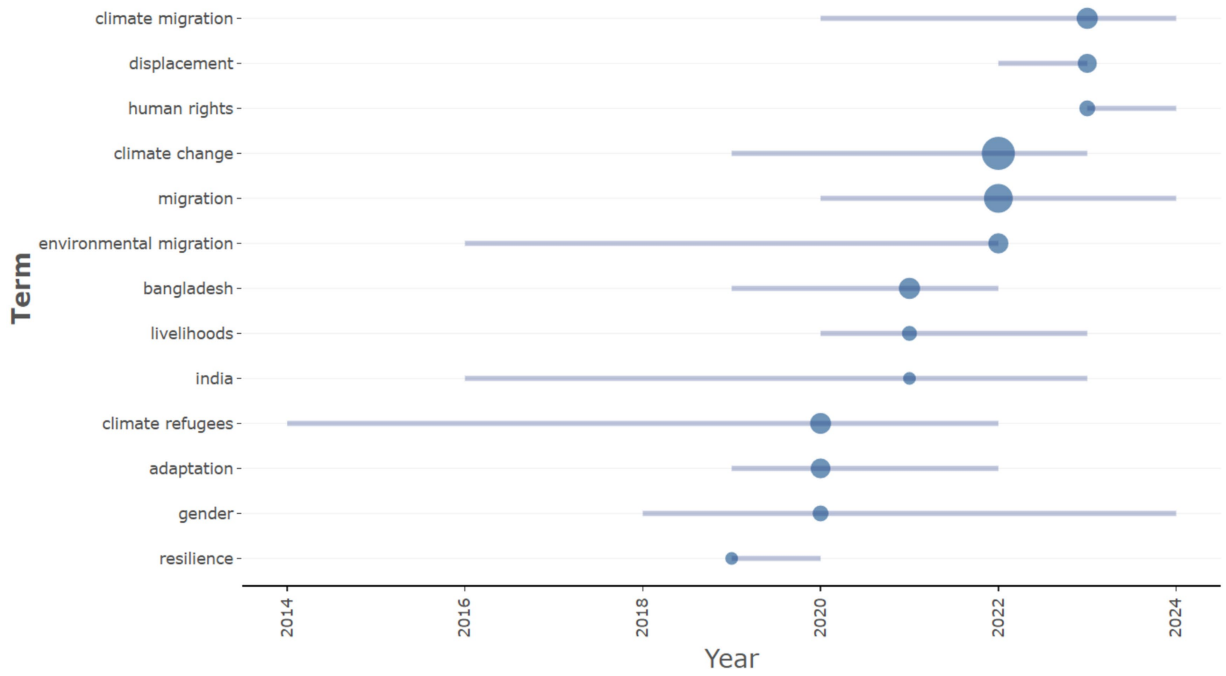


FIGURE 9
Distribution of trending topics.

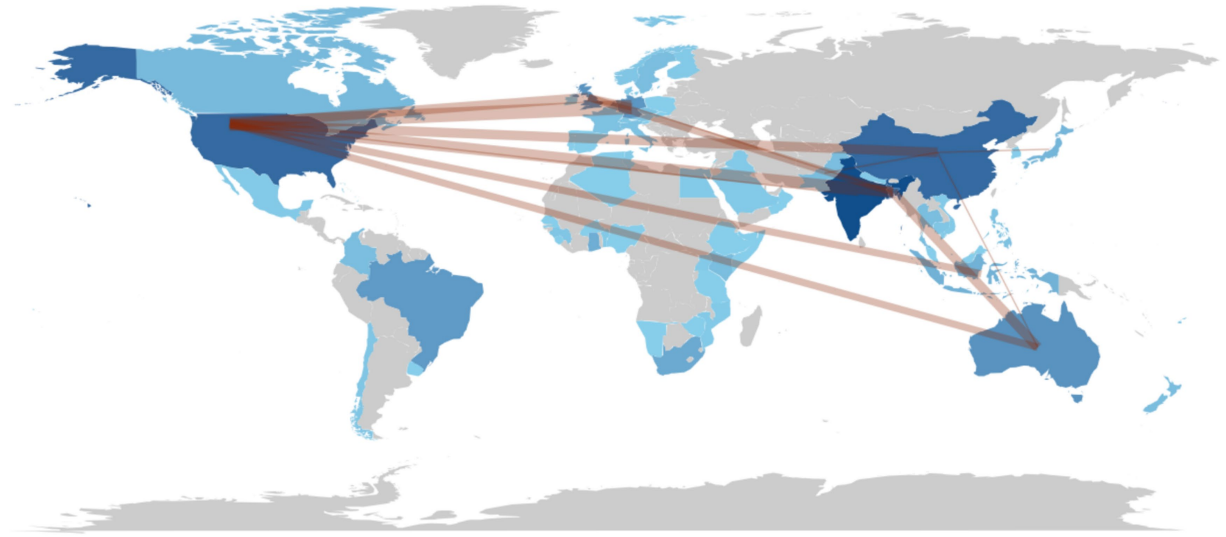


FIGURE 10
Global collaboration map.

climate change and migration are key issues but require further attention. These are widely discussed themes but there is room for thorough engagement in policy and research.

The Bottom Left Quadrant is known as an emerging theme, consisting of underdeveloped topics that might be gaining or losing attention. A network will gradually develop topics such as climate migration, mobility, West African and extreme events. These themes either need more research attention or are becoming less central to the current discourse.

Figure 12 depicts the co-citation network of authors. The visualization created by VOSviewer includes authors who have been cited at least 15 times. Authors are grouped into three distinct clusters while each representing different thematic contributions within the field. The red cluster includes authors such as Richard Black, W. Neil Adger, and Robert A. McLeman, who are prominent figures in climate migration, environmental change, and human mobility research. Their research interests lie in adaptation, displacement, resilience, and policy responses. The green cluster includes Ingrid Boas, François

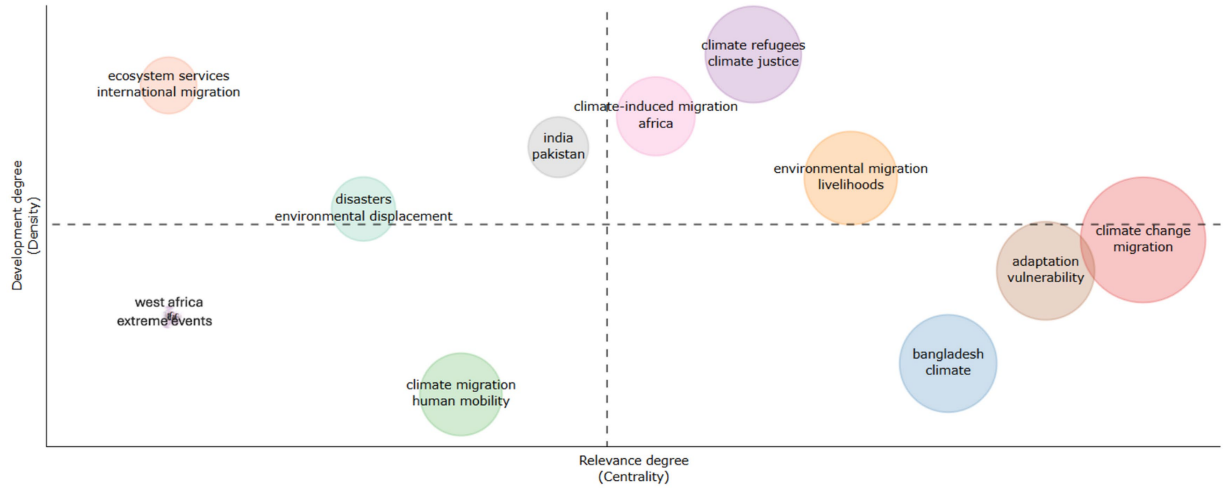


FIGURE 11
Thematic map based on author keywords.

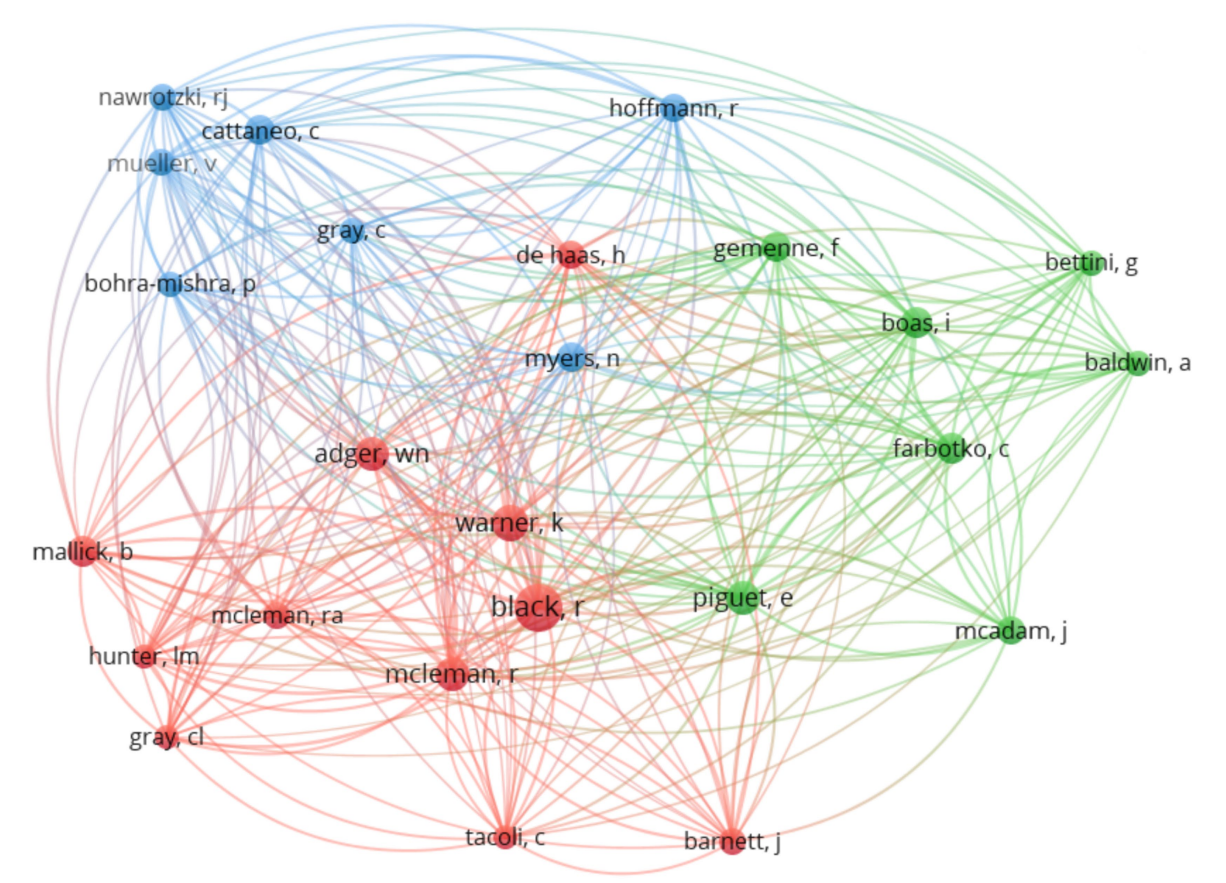


FIGURE 12
Co-citation analysis of authors.

Gemenne, and Jane McAdam who are primarily linked to governance, policy frameworks, and the socio-political dimensions of climate migration. These authors work on climate justice, legal frameworks, and institutional responses to migration. The blue cluster is represented by authors Cristina Cattaneo, Clark Gray, and Raphael Nawrotzki, who are focused on empirical studies, statistical modeling, and economic perspectives on migration and environmental stressors. They often utilize quantitative methods to assess migration drivers and

decision-making processes. Cluster composition reveals agenda-setting by Global-North institutions in legal/normative and econometric strands; bridging these with Southern empirics and community-based methods is essential to avoid reproducing extractive knowledge dynamics.

Discussion

The trend in average citations per document from 2004 to 2024, as shown in Figure 3, reflects not only the evolving academic interest in climate-induced migration in the Global South but also illustrates deeper structural inequalities in global knowledge production. The sharp rise in citations post-2012, peaking in 2018, aligns with critical global events and policy developments that elevated the topic in academic and policy circles. The Paris Agreement (2015) brought climate-induced displacement to the international policy agenda, while devastating climate events in the Global South, such as the 2016 Cyclone Winston in Fiji and major floods in South Asia, stimulated scholarly and humanitarian interest. Influential works during this period, including those by Cai et al. (2016) on climate-migration linkages via agriculture, Berchin et al. (2017) advocating legal recognition of climate refugees, and Bettini et al. (2017) critiquing injustice in migration discourse, became widely cited across disciplines. These contributions marked a shift toward more justice-centered and nuanced conceptualizations of climate mobility, incorporating lenses of vulnerability, agency, and intersectionality (Black et al., 2011; Radel et al., 2018; McLeod et al., 2018).

The decline in citations after 2018 does not necessarily indicate waning interest but can be largely attributed to citation lag, as publications from 2022 to 2024 have not had sufficient time to accrue citations (Donthu et al., 2021). More importantly, it reveals enduring citation inequities. As Arruda Filho et al. (2024) and Milán-García et al. (2021) observe, Global North scholars and institutions continue to dominate both publication and citation counts, even though the empirical focus is often on the Global South. This epistemic imbalance is a central concern in climate justice scholarship, which critiques the marginalization of Southern knowledge systems and calls for greater visibility of Global South scholars and community-driven research (Anjum and Aziz, 2025a,b; Bettini et al., 2017). While the number of studies led by authors from institutions in Africa, South Asia, and Latin America is increasing, these still face barriers in accessing high-impact journals and citation networks.

Figure 4 maps the temporal publication activity of the top 10 most productive authors in climate-induced migration research, revealing patterns that reflect broader climate justice dynamics in academic knowledge production. Mallick Bishawjit emerges as the most prolific recent contributor, especially post-2019, through his empirically grounded work in South Asia, emphasizing justice-centered adaptation and relocation (Mallick and Etzold, 2015; Mallick and Schanze, 2020). Mayer Benoît, a key contributor in 2013, remains influential for pioneering legal critiques of refugee protection gaps under climate stress (Mayer, 2013, 2016). Authors like Byravan Sujatha and Bezu Sosina have maintained sustained contributions; Byravan's research advocates for dignity in planned relocation (Byravan and Rajan, 2015), while Bezu's Ethiopia-focused work reveals intersectional vulnerabilities in youth and smallholder migration (Bezu and Holden, 2014). Emerging scholars such as Banerjee, Bruton-Adams, and Carte reflect a recent diversification of themes and perspectives, particularly those aligned with feminist and postcolonial approaches (McLeod et al., 2018; Morrison et al., 2023).

This post-2019 uptick in author productivity underscores a maturing and expanding field, yet it also exposes persistent epistemic inequalities. Most highly cited and visible authors remain affiliated with Global North institutions, despite the research being grounded in Global South realities—an imbalance critiqued in recent bibliometric reviews (Milán-García et al., 2021; Arruda Filho et al., 2024). As Anjum and Aziz (2025a) note, the dominance of Northern epistemologies in climate justice research sidelines Southern perspectives. These citation and authorship hierarchies risk reinforcing colonial knowledge dynamics and must be addressed by promoting South–South collaboration, inclusive citation practices, and recognition of indigenous and community knowledge.

The author and institutional trends presented in Figure 4 and Table 3 reflect a promising expansion of climate-induced migration research, particularly from the Global South. Scholars like Mallick Bishawjit and Bezu Sosina have made sustained, justice-oriented contributions rooted in local contexts, while institutions such as Hohai University, Makerere University, and Shahjalal University demonstrate growing regional leadership. This diversification marks a positive shift toward more inclusive and grounded scholarship. However, consistent with critiques from climate justice literature (e.g., Anjum and Aziz, 2025a; Bettini et al., 2017), Global South institutions and scholars still face structural barriers in accessing global research networks and shaping dominant narratives. Overall, the findings highlight an increasingly vibrant and geographically diverse field, while underscoring the continued need for equitable collaborations, recognition, and funding structures that empower Global South leadership.

Figure 5 illustrates the geographic distribution of corresponding authors in climate-induced migration research, distinguishing between Single Country Publications (SCP) and Multiple Country Publications (MCP). The highest publication volumes originate from India, China, and Bangladesh, with a predominant focus on SCP, suggesting strong domestic research capacities but limited international integration. This pattern is critical from a climate justice perspective, as it reflects both the strengths and constraints of Global South scholarship. While these countries are among the most affected by climate-induced migration (Rigaud et al., 2018), their limited participation in transnational research collaborations points to structural barriers in funding access, institutional networks, and linguistic capital, reinforcing long-standing North–South knowledge hierarchies (Arruda Filho et al., 2024; Anjum and Aziz, 2025a). The case of Brazil, whose corresponding authors exclusively published via SCP, exemplifies this phenomenon despite the country's significant exposure to environmental displacement in the Amazon and northeast regions.

Conversely, Global North countries—USA, UK, Germany, and Australia—display a higher share of MCPs, reflecting dominant roles in agenda-setting, funding flows, and authorship hierarchies. For instance, the UK and USA, while producing fewer total publications than India and China, appear more integrated in cross-national research networks. This dynamic echoes critiques by Bettini et al. (2017) and Milán-García et al. (2021), who show how North-based institutions often lead collaborative projects even on Global South issues, potentially shaping narratives and research priorities. Australia's

exclusive involvement in MCPs indicates a policy-science nexus that leans heavily on international engagement, possibly linked to its geopolitical focus on the Pacific, a region facing existential threats due to climate-induced migration (McLeod et al., 2018; Morrison et al., 2023).

Figure 6 reveals notable geographical patterns in the scientific production of climate-induced migration research, with particularly high output from China (70 articles), the USA (57), and India (54). The growing participation of countries such as Bangladesh (44) and the UK (32) also reflects an expanding and increasingly internationalized field. This growth in Global South scholarship, particularly from India and Bangladesh, is commendable, as it brings attention to frontline regions where climate impacts and migratory pressures are already acute. However, a climate justice lens requires critical engagement not just with the quantity of publications, but with whose knowledge is produced, disseminated, and cited. While China and India have high publication volumes, their average citations per article remain lower (17.1 and 10.7 respectively) compared to the USA (37.6), the UK (26), and even smaller contributors like Poland (25) and Pakistan (20). This disparity suggests ongoing structural citation inequities, where Global South knowledge is often less recognized in dominant academic discourse (Milán-García et al., 2021; Arruda Filho et al., 2024).

These patterns echo concerns in climate justice scholarship about epistemic inequality and the coloniality of knowledge production. For instance, Anjum and Aziz (2025c) emphasize that even when research is rooted in Global South contexts, citations, influence, and policy uptake tend to favor Global North institutions. This is reinforced by Bettini et al. (2017), who critique how Northern-centric narratives often overshadow context-sensitive, justice-oriented research emerging from the Global South. Moreover, although the USA leads in both total and average citations, much of its research focuses on other regions, raising concerns about positionality, representation, and power asymmetries. In contrast, countries like Bangladesh and Pakistan, despite their vulnerability, produce fewer high-impact papers, often due to barriers in accessing elite journals, funding, and transnational collaborations. These results suggest the urgent need to recognize and amplify Southern epistemologies, promote inclusive citation practices, and ensure that those most affected by climate displacement are not only research subjects but also leading voices in the global academic and policy arenas.

Table 4 showcases a strong and evolving foundation of high-impact scholarship on climate-induced migration, led by widely cited works such as Cai et al. (2016) and Jha et al. (2018), which establish critical empirical linkages between environmental stressors and migration, especially in agriculture-dependent regions. Notably, studies like Bettini et al. (2017) and Radel et al. (2018) enrich the discourse by embedding climate migration within broader justice and political ecology frameworks, while McLeod et al. (2018, 2019) foreground Indigenous and gendered perspectives from the Pacific Islands, aligning with the decolonial aims of climate justice. The inclusion of newer works such as Guo et al. (2022) reflects the field's responsiveness to emerging drivers like air pollution. This collection of literature, with over 760 citations in total, is commendable not only for its scholarly depth but also for its increasing orientation toward equity, intersectionality, and community-centered adaptation, demonstrating meaningful progress toward a more justice-oriented and inclusive research landscape.

Table 5 highlights the distribution of influential journals in climate-induced migration research, revealing both the visibility of the field and the dynamics of knowledge dissemination. From a climate justice perspective, the presence of journals such as Climatic Change, International Journal of Climate Change Strategies and Management, and Climate and Development—with a combined total of 17 articles and over 360 citations—indicates growing academic engagement with the complex interplay between environmental stressors, displacement, and human rights. Notably, the International Journal of Climate Change Strategies and Management stands out with only five publications but the highest total citations (202), suggesting that its content is especially impactful, likely due to its focus on adaptation strategies and policy integration, themes central to justice-oriented responses (Jha et al., 2018; Berchin et al., 2017).

The dominance of mainstream publishers such as Springer, Taylor & Francis, and Elsevier, while reflecting academic rigor, also underscores concerns raised in climate justice scholarship about restricted access and global inequalities in publication visibility and affordability (Anjum and Aziz, 2025c; Arruda Filho et al., 2024). Journals like Sustainability (MDPI), which offer open access, are playing an important democratizing role with six publications and 87 citations, helping to amplify voices from the Global South and increase accessibility for underfunded institutions. Importantly, the inclusion of regionally focused journals such as Asian Population Studies and Economic and Political Weekly—both publishing fewer but impactful studies—illustrates efforts to engage with localized, community-based, and often underrepresented perspectives on migration and vulnerability (McLeod et al., 2018; Radel et al., 2018).

Figure 2 and Table 2 present a co-occurrence network of author keywords, illustrating four thematic clusters that define the intellectual structure of climate-induced migration research. The red cluster centers on climate change, adaptation, and vulnerability, interlinked with gender, livelihoods, resilience, and Sub-Saharan Africa. This grouping emphasizes justice-oriented concerns around exposure, coping capacity, and intersectionality, especially in Global South contexts (McLeod et al., 2018; Radel et al., 2018). The green cluster focuses on migration, climate refugees, climate justice, and human rights, highlighting a normative and rights-based turn in the field that critiques securitized framings and foregrounds dignity, equity, and historical responsibility (Bettini et al., 2017; Mayer, 2016; Berchin et al., 2017). Together, these clusters reflect a broadening of the field from empirical assessments of mobility to ethical and legal frameworks, signaling increasing alignment with the principles of climate justice.

Figure 9 maps the temporal evolution of key terms in climate-induced migration research and reveals a shift from early environmental determinism toward a more nuanced, justice-oriented discourse. Terms like "environmental migration" and "climate refugees" were dominant in the early years, particularly around 2014–2016, reflecting the initial framing of climate migration as an inevitable outcome of environmental change. However, these framings have been widely critiqued for their securitized and decontextualized narratives, which risk undermining the agency of affected populations and oversimplifying complex socio-political drivers (Bettini et al., 2017; Mayer, 2016). In contrast, recent years—especially post-2020—have seen a marked rise in the usage of terms such as "displacement," "human rights," and "climate migration," indicating a shift toward

more legal, social, and ethical considerations, in line with the principles of climate justice (Berchin et al., 2017; McLeod et al., 2018).

Simultaneously, the growing presence of terms like "resilience," "adaptation," "gender," and "livelihoods" points to an increasing concern with structural vulnerability, intersectionality, and local agency in shaping mobility outcomes (Radel et al., 2018; Morrison et al., 2023). The emphasis on "gender" and "livelihoods" particularly signals engagement with feminist and community-based perspectives, which advocate for recognition of how climate stress intersects with social roles, economic insecurity, and historical marginalization (McLeod et al., 2018; Anjum and Aziz, 2025b). The recent surge in "human rights" discourse reflects ongoing advocacy for formal legal protection for climate-displaced persons, and a movement away from crisis narratives toward rights-based and participatory approaches. Overall, this evolution demonstrates encouraging progress in the field—moving from reactive and technocratic framings to critical, inclusive, and justice-informed paradigms that better reflect the lived realities of vulnerable populations in the Global South (Anjum and Aziz, 2025a; Aziz and Anjum, 2024).

Figure 10 reveals the global architecture of scholarly collaboration in climate-induced migration research, underscoring a persistent North–South asymmetry in knowledge production networks. The United States stands out as the dominant hub, collaborating extensively with China, India, Bangladesh, the UK, and Australia. While such partnerships have contributed to increased scholarly output and funding access, they often follow patterns of asymmetric power, where Global North institutions control research agendas, lead authorship, and determine publication venues, even when studies focus on Global South contexts (Anjum and Aziz, 2025a; Arruda Filho et al., 2024). This pattern reinforces epistemic hierarchies that climate justice scholars' critique as replicating colonial modes of knowledge extraction, where affected communities and Southern scholars are positioned as data providers rather than co-producers of knowledge (Bettini et al., 2017; Aziz and Anjum, 2025).

Though countries like China, India, and Australia are emerging as productive contributors, the figure shows limited South–South collaboration, with most research partnerships still mediated through Global North institutions such as those in the USA, UK, and Germany. This reflects broader critiques in climate justice and development literature regarding the lack of horizontal, equitable research networks among Global South regions, which share similar climate vulnerabilities and socio-political constraints but are rarely given space to collaborate directly (Milán-García et al., 2021; Morrison et al., 2023). For instance, despite their shared experiences with displacement and adaptation, countries like Bangladesh and Kenya, or India and the Philippines, are rarely seen in direct collaboration. Addressing this gap is crucial not only for ensuring context-sensitive and inclusive research, but also for empowering Southern institutions to reshape the theoretical, methodological, and policy discourse on climate migration from within. Moving forward, fostering South–South knowledge solidarity and challenging North-led epistemic dominance must be central to a climate justice-informed research agenda.

Figure 11 presents a thematic map of climate-induced migration research using author keywords, structured along two axes: centrality (relevance to the field) and density (degree of development). The upper right quadrant (Motor Themes) includes climate change, migration, adaptation, vulnerability, and environmental migration with livelihoods, reflecting well-developed and central topics that dominate scholarly and policy debates. These themes represent the core of climate justice discourse, focusing on both structural drivers and human agency in contexts of environmental stress (Bettini et al., 2017; Gemenne and Blocher, 2017). The presence of adaptation and livelihoods in this quadrant signifies a shift from reactive framings toward resilience-building and justice-based strategies that prioritize agency, equity, and systemic transformation (McLeod et al., 2018; Radel et al., 2018).

In the upper left quadrant (Highly Developed but Peripheral Themes), we find ecosystem services and international migration. These are specialized and technically mature themes, but less central to the current climate migration discourse. Their marginality may reflect a lack of integration with justice-centered and community-based approaches, even though ecosystem degradation and cross-border migration are critical issues, especially in regions affected by ecological collapse and political instability (Morrison et al., 2023). The lower right quadrant (Basic and Transversal Themes), including climate-induced migration, climate refugees, and climate justice, demonstrates that these topics are highly relevant but still underdeveloped in their theoretical integration and empirical breadth—pointing to the need for deeper interdisciplinary engagement and South-led frameworks (Anjum and Aziz, 2025a; Mayer, 2016). Meanwhile, the lower left quadrant (Emerging or Declining Themes)—with terms like West Africa, extreme events, and human mobility—represents areas requiring renewed focus. Although these topics are crucial for understanding contextual vulnerability and acute shocks, their marginal status reveals ongoing geographical and thematic blind spots in dominant literature (Arruda Filho et al., 2024; Milán-García et al., 2021). As climate impacts intensify, it is essential for research to center these neglected themes and ensure that underrepresented regions and framings are brought into the mainstream of climate migration scholarship.

Figure 12 maps the co-citation network of influential authors in climate-induced migration research, organized into three thematic clusters that reflect distinct scholarly orientations within the field. The red cluster, featuring prominent figures like Richard Black, W. Neil Adger, and Robert A. McLeman, is grounded in research on human mobility, adaptation, and environmental change. These authors have been central to conceptualizing migration as both a coping strategy and adaptation mechanism in response to environmental stressors (Black et al., 2011; Adger et al., 2014). Their work emphasizes structural vulnerability, policy responses, and the role of resilience, aligning closely with climate justice principles that advocate for agency-driven and context-specific solutions (Mallick and Etzold, 2015; McLeman, 2018). The presence of Md. Bishawjit Mallick in this cluster further strengthens its justice orientation, particularly through his contributions from a Global South perspective on trapped populations, relocation, and community adaptation (Mallick and Schanze, 2020).

The green cluster, anchored by authors such as François Gemenne, Ingrid Boas, and Jane McAdam, brings a legal, governance, and normative focus to the field. These scholars engage with climate justice, human rights, and institutional accountability, often critiquing the inadequacies of current legal regimes to protect climate-displaced populations (McAdam, 2011; Boas et al., 2019). Their work underscores the need to move beyond securitized or apolitical framings toward rights-based and participatory frameworks, calling

for institutional reform and equitable governance structures (Bettini et al., 2017; Gemenne and Blocher, 2017). The green cluster reflects a vital strand of scholarship that situates climate migration within broader questions of power, colonial legacies, and global inequality, thus advancing the normative core of climate justice.

In contrast, the blue cluster, comprising authors such as Cristina Cattaneo, Clark Gray, Raphael Nawrotzki, and Valerie Mueller, is characterized by quantitative, empirical approaches. These scholars have contributed rigorous econometric and demographic analyses of migration drivers, often linking temperature variations, rainfall shocks, and agricultural productivity with mobility outcomes (Cattaneo and Peri, 2016; Nawrotzki and DeWaard, 2016). While this work provides essential insights into causality and migration decision-making, it has been critiqued by justice scholars for sometimes lacking contextual depth and critical engagement with political structures (Bettini et al., 2017). Nonetheless, the increasing integration of these empirical approaches with justice-oriented frameworks holds promise for evidence-based, policy-relevant, and ethically grounded research.

Implications for the climate justice–migration nexus

Our bibliometric findings underscore that climate justice and migration are deeply interconnected but often unevenly articulated in scholarly discourse. Justice-related terms such as *climate justice*, *human rights*, *gender*, and *livelihoods* emerged as significant clusters in keyword and thematic analyses, demonstrating that the justice–migration nexus is empirically visible across the literature. However, the prominence of Global North authorship and thin South–South collaboration reflects persistent distributive and recognition inequities. Thematic gaps in *procedural justice* (e.g., inclusive participation in relocation planning) and *reparative justice* (e.g., linking historical emissions to displacement responsibilities) highlight areas where the field remains underdeveloped. These findings suggest that future research must not only document mobility patterns but also interrogate the justice dimensions shaping who migrates, under what conditions, and with what rights. By foregrounding climate justice, our study reframes migration from being understood merely as a risk management issue to being recognized as a justice-laden process that reflects deeper structural inequities in global governance.

Another limitation stems from linguistic and indexing constraints. As the analysis only includes English-language publications, contributions in regional languages remain unaccounted for. Furthermore, emerging terms like 'climate mobilities' and 'immobility' may not have been fully captured due to keyword design. These gaps should be explored in future multilingual or mixed-method reviews.

Gaps and opportunities for future research

While climate-induced migration has gained scholarly momentum, key gaps remain that limit both conceptual completeness and the development of just, effective policies. Geographical blind spots persist regions like Central Africa, the Middle East, interior Latin America, and Indian Ocean island states remain underexplored, despite their acute vulnerabilities (e.g., drought-induced rural–urban migration in Sudan or Iran). Within well-studied countries, marginalized groups—such as Indigenous peoples, remote rural communities, and urban informal migrants—are often overlooked. Moreover, migrant destinations are understudied; research tends to focus on departure zones rather than outcomes in host cities (jobs, health, integration).

There is also a growing need to explore mobility trajectories and immobility—including stepwise migration patterns and the plight of "trapped" populations who cannot or choose not to move. Meanwhile, stronger cross-disciplinary integration is essential. Climate science, migration modeling, political science, anthropology, and decolonial theory must be better synthesized to capture the complexity of displacement. Advancing climate attribution methods to quantify migration directly linked to anthropogenic climate change will also reinforce climate justice claims by connecting emissions to displacement. Similarly, policy evaluation research should assess the effectiveness of adaptation, relocation, and migration-as-adaptation interventions to guide future action.

Data scarcity remains a challenge; however, new tools like remote sensing, mobile data, and citizen science offer promising solutions—if used ethically. Research must also address intersectionality, recognizing how gender, age, class, and ability shape migration experiences and adaptation capacity. Lastly, while crisis dominates the discourse, future research should also explore positive migration outcomes, identifying cases where mobility has improved wellbeing or reduced environmental strain. Ultimately, addressing these gaps requires interdisciplinary collaboration, ethical innovation, and Global South leadership, ensuring climate migration scholarship serves equity, justice, and resilience (Anjum and Aziz, 2024).

In essence, the gaps point to a need for more granular, inclusive, and forward-looking research. Bridging these gaps will require collaboration across disciplines and with practitioners, as well as elevating voices from the Global South in setting research agendas. Filling these knowledge gaps will directly inform more just and effective solutions.

Conclusion

This bibliometric analysis of climate-induced migration research in the Global South, viewed through a climate justice lens, reveals a rapidly evolving and increasingly interdisciplinary field. The study analyzed 204 documents spanning two decades (2000–2024), mapping trends in authorship, publication, thematic evolution, and geographic focus. Citation patterns suggest that foundational works—largely published prior to 2020—continue to dominate influence, while newer studies, especially those from the Global South, remain under-cited.

The analysis identified key thematic clusters—such as climate change, displacement, adaptation, and human rights—indicating a welcome shift from narrow crisis narratives to broader, justice-oriented frameworks. Scholars like François Gemenne, Ingrid Boas, Richard Black, and Bishawjit Mallick have contributed significantly to shaping debates across empirical, legal, and normative domains. Nevertheless, epistemic asymmetries persist: Global North institutions continue to dominate collaborative networks and high-impact publications, even though much of the empirical focus lies in the Global South. Thematic maps and network analyses reveal emerging interest in intersectionality, gender, and immobility, but these areas

remain underdeveloped. Moreover, the data highlight a lack of sustained South–South collaboration, limited integration of Indigenous knowledge systems, and insufficient research on migration destinations and livelihood outcomes.

From a climate justice perspective, the current research landscape is expanding in promising directions but remains constrained by structural imbalances in authorship, representation, and access. Addressing these gaps will require a reorientation toward inclusive and decolonial knowledge production—where Global South scholars are not just contributors, but agenda-setters. Future research should integrate interdisciplinary methods, strengthen links between empirical evidence and legal frameworks, and foreground the lived realities and voices of displaced populations. Critically, it must also challenge dominant narratives by incorporating historical accountability, relational vulnerability, and the political economy of migration.

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

MA: Funding acquisition, Writing – original draft, Supervision, Writing – review & editing, Investigation, Software, Resources, Formal analysis, Data curation, Project administration, Visualization, Conceptualization, Validation, Methodology. GA: Supervision, Conceptualization, Writing – review & editing, Methodology, Data curation. AN: Resources, Writing – original draft, Software, Methodology, Visualization, Formal analysis, Data curation. IN: Investigation, Resources, Writing – review & editing, Visualization, Supervision, Data curation.

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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.

Generative AI statement

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Building Africa's climate resilience: understanding the impacts and future strategies in the face of climate change

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Climate change is reshaping Africa's environmental, economic, and social landscapes, intensifying vulnerabilities across agriculture, water resources, public health, and socioeconomic stability. This paper examines the multifaceted impacts of a changing climate on key sectors in Africa and highlights the urgent need for integrated adaptation strategies. Through the synthesis of traditional wisdom and modern innovations, the study showcases how indigenous knowledge, community-led initiatives, and climate-smart agricultural practices contribute to enhanced resilience. Case studies from diverse regions demonstrate the effectiveness of combining traditional practices with advanced technologies, while policy and governance frameworks emphasize the importance of inclusive, data-driven decision-making. The research further addresses critical investment gaps and advocates for robust financial and technical support to empower local communities in managing climate risks. By leveraging established frameworks such as the African Climate Resilience Acceleration roadmap and fostering cross-sectoral collaboration, the paper outlines forward-looking strategies that could mitigate immediate climate threats and lay the groundwork for sustainable development. Ultimately, through coordinated efforts and strategic investments, African nations can transform the challenges of climate change into opportunities for resilience and growth.

KEYWORDS

climate change adaptation, Africa's resilience, indigenous knowledge, climate-smart agriculture, sustainable development, community-based adaptation

1 Introduction

Africa faces a critical challenge: climate change, which profoundly disrupts its social, economic, and environmental systems. With over 60% of its population relying on climate-sensitive sectors like agriculture, increasing variability along with frequent extreme weather events now jeopardizes food security and livelihoods (Teklu et al., 2023). As human-induced factors and natural variability continue to alter climate patterns, community vulnerability, especially among marginalized groups, grows (Badolo, 2024). In light of these changes, the Intergovernmental Panel on Climate Change (IPCC) projects that Africa will experience rising temperatures, altered precipitation regimes, and more frequent extremes, such as droughts and floods (Wright et al., 2024).

The impacts of climate change extend well beyond agriculture. Intensified climate variability, including hotter extremes, erratic rainfall, and a surge in severe weather events, threatens fisheries, water resources, public health, and overall socio-economic stability (Vijai

et al., 2023; Selvaraju et al., 2011). In agriculture, these uncertainties have been linked to reduced crop yields, disrupted supply chains, and heightened food insecurity that imperils millions of rural households (Pimpa, 2024). Likewise, shifts in temperature and rainfall patterns are undermining fisheries and water management systems, leading to diminished fish stocks and compromised freshwater availability (Ibrahim, 2025; Khakimov et al., 2020). Collectively, these multidisciplinary challenges underscore the urgency of designing robust adaptation strategies and integrated risk management approaches to secure both agricultural and broader food systems against the adverse effects of a changing climate (Giannini et al., 2021; Amare and Simane, 2017).

Building climate resilience is essential for the continent's sustainable development. Climate resilience is defined as the capacity of individuals, communities, and systems to anticipate, prepare for, and rebound from climate-related disruptions (Weldegebriel and Amphune, 2017). Many African communities have historically relied on traditional ecological knowledge, developing adaptive strategies over generations (Asmamaw et al., 2019). However, the rapidly evolving nature of climate change calls for multifaceted approaches that integrate these traditional methods with modern agricultural techniques and climate-smart practices, thereby enhancing the adaptive capacity of vulnerable populations (Graham, 2020).

A range of practical measures is essential to build resilience among smallholder farmers and rural communities in Africa. Early warning systems and decision-support tools, for instance, enable timely adjustments to changing climatic conditions (Mthembu and Zwane, 2017), while the innovative Water-Energy-Food Nexus framework transforms rural livelihoods by addressing critical interdependencies to reduce vulnerability (Mabhaudhi et al., 2019). Empowering local communities to adopt new technologies enhances an inclusive approach to resilience building (Gould and Rudolph, 2015), and integrating public health considerations is critical as rural health service managers anticipate mounting climate-related challenges (Purcell and McGirr, 2017). Ultimately, a collaborative strategy that merges scientific research, indigenous knowledge, and health perspectives, and accounts for gender dynamics, local governance, and economic policies, is indispensable for creating resilient systems across Africa (Popoola et al., 2020; Rankoana, 2023; Adzawla et al., 2019; Khoza et al., 2021).

In practice, integrating early warning systems with decision-support mechanisms plays a vital role in alerting farmers to imminent hazards and facilitating timely adaptation. Advanced notifications of droughts, floods, and other extreme events allow for efficient resource mobilization, reallocation of inputs, and adjustments to cropping calendars (Antwi-Agyei and Nyantakyi-Frimpong, 2021; Sarr and Sultan, 2022), while coupling these tools with information and communication technologies enhances forecast precision and risk assessment (Chen et al., 2023; Meechang et al., 2020). Moreover, effective implementation of such systems fosters community engagement and builds trust in climate services, spurring proactive responses and long-term strategic planning, like altering planting schedules and diversifying crop varieties, to reduce exposure to climate hazards and support sustainable agricultural practices (Agbehadji et al., 2023).

This study provides an innovative analysis of climate change impacts across Africa by addressing critical gaps in our understanding of adaptation processes. Moving beyond earlier research that has examined isolated aspects of climate change, our work synthesizes indigenous knowledge with modern scientific insights to develop comprehensive adaptation strategies, responding to calls for merging traditional wisdom with contemporary methods (Nyadzi et al., 2021; Ajani et al., 2013). Central to our approach is the creation of innovative governance and policy frameworks tailored to local contexts, reflecting evidence that context-specific measures and locally driven initiatives are vital for enhancing resilience in under-resourced communities (Sesugh Aule, 2025; Adebola, 2024). By addressing a continent-wide challenge, our study transcends narrow sectoral responses and presents integrative methods to bolster climate resilience. Recent work illustrates that indigenous strategies can significantly contribute to disaster risk reduction (Motsumi and Nemakonde, 2024) and that community-led adaptations effectively buffer climatic variability (Ajani et al., 2013). Furthermore, studies by Mercer et al. (2010) and Datta and Kairy (2024) underscore the importance of centering traditional knowledge in policy-making, while Shammin et al. (2021) reported that community-based models demonstrate the benefits of blending indigenous practices with modern governance structures. Together, these insights support our novel, holistic framework for addressing the multifaceted challenges posed by climate change across Africa.

The primary aim of this study is to explore the multifaceted impacts of climate change across Africa and to identify effective strategies for strengthening the continent's resilience. To achieve this aim, the study pursues three specific objectives: (1) evaluate the vulnerability of critical sectors such as agriculture, health, and water resources, by examining how climate change exacerbates existing challenges; (2) identify, categorize, and critically evaluate effective adaptation strategies currently employed in various African communities; and (3) examine the prevailing governance and policy frameworks that guide climate resilience initiatives. By fostering a multidimensional approach that combines traditional knowledge with modern adaptations, this paper advances the dialogue on sustainable development in Africa and paves the way for more effective strategies to create a resilient future.

2 Climate change vulnerability in Africa

Africa remains one of the most climate-vulnerable regions globally, facing unique susceptibilities compared to more economically diversified areas. Its diverse landscapes and economies are frequently exposed to extreme weather events, and, unlike many other regions, Africa's heavy reliance on climate-sensitive sectors, particularly agriculture, renders it especially susceptible to adverse impacts. This vulnerability is further compounded by pervasive socio-economic challenges, limited infrastructural development, and constrained financial resources, all hindering effective adaptation. A comprehensive understanding of these distinctive climate risks is essential for developing targeted strategies that boost resilience and promote sustainable development amid escalating climate challenges.

2.1 Regional exposure and adaptive capacity

Across Africa, climate vulnerability is intensified by widespread dependence on rain-fed agriculture, which underpins the livelihoods of millions (Ayodotun et al., 2019). In West Africa, projections indicate that rising temperatures, erratic rainfall, and recurrent droughts will increasingly subject communities to compound events, such as simultaneous heatwaves and heavy precipitation, that imperil food security and public health (Quenum et al., 2021; Weber et al., 2020). Similarly, countries across sub-Saharan Africa including Sudan, Niger, and Ethiopia are already experiencing dramatic shifts in precipitation and rising temperature anomalies that undermine agricultural productivity and strain water resources (Adzawla et al., 2019; Smith et al., 2023). These physical challenges are further exacerbated by socio-economic constraints such as persistent poverty, limited access to education, healthcare, technology, and an overreliance on subsistence farming (Aryana et al., 2024; Blennow and Persson, 2021). Institutional shortcomings, inadequate infrastructure, and insufficient investment in adaptive technologies, coupled with social issues like gender inequality and the marginalization of vulnerable groups, further hinder effective climate resilience, making urgent and systematic interventions essential (Giarola et al., 2022; Binuyo et al., 2022).

Annual fluctuations in precipitation and evolving temperature trends offer additional insight into Africa's escalating climate risks. Despite a broadly consistent precipitation cycle across the continent, significant interannual variability emerges, particularly in southern Africa, where declining mean annual rainfall and increased variability have led to drier conditions and elevated risk of extreme events (Samuel et al., 2024; Gaughan et al., 2015). Concurrently, a steady rise in annual mean temperatures over recent decades further stresses agriculture and water resources already challenged by erratic rainfall (Neate-Clegg et al., 2021). Model simulations based on the CMIP6 framework project indicate that increasing temperature anomalies will worsen moisture deficits and heighten the frequency of extreme hydrometeorological events (Almazroui et al., 2020). However, persistent uncertainties in observational reanalysis datasets, particularly regarding precipitation, underscore the need for ongoing refinement in both data collection and modeling techniques (Gleixner et al., 2020). Collectively, these shifting climatic patterns necessitate adaptive strategies and integrated policy responses tailored to the unique vulnerabilities of Africa (Samuel et al., 2024).

2.2 Multi-hazard mapping of climate extremes

We built a 10 km resolution vulnerability atlas of Africa for 2000–2024 using Google Earth Engine. Daily MOPlDIS surface-temperature layers were transformed into heatwave-frequency rasters, and CHIRPS rainfall records were converted into drought- and flood-frequency images following thresholds defined by Eze and Siegmund (2024). Gaps in these time series were filled with ERA5 reanalysis to ensure temporal continuity, as outlined by Heydari et al. (2024). Each hazard layer was then normalized via min-max scaling to align disparate units and suppress extreme outliers before computing an equal-weighted composite index. The resulting country scores and high-resolution maps appear in Figure 1a and Supplementary Table S1, while subnational patterns are detailed in Figure 1b.

Country-level vulnerability indices range from 0.0 in Morocco, Algeria, Tunisia, Libya, and Egypt to a maximum of 1.92 in Sierra Leone, Liberia, Côte d'Ivoire, Ghana, and Nigeria (Figure 1a). Central African Republic and select provinces of the Democratic Republic of the Congo also exceed 1.0, and Southern African nations like Angola, Zambia, Malawi, Zimbabwe, and Botswana populate the upper half of the vulnerability spectrum. Supplementary Table S1 provides the full list of national scores, highlighting how West African and parts of Central and Southern Africa bear the heaviest cumulative risk, whereas North Africa remains comparatively sheltered.

Despite these national averages, Figure 1b exposes striking subnational disparities. In Sudan and Chad, several northern provinces record vulnerability values upward of 1.5, far outstripping their national means. Kenya's northern and coastal counties likewise surpass the country's aggregate index, and eastern districts in South Africa reveal vulnerability pockets hidden beneath its moderate national score. Liverman (2024) attributes much of this spatial heterogeneity to geographic diversity, ranging from Sahelian heat extremes to equatorial flood regimes, while Cutter et al. (2003) demonstrate how local topography and land cover can amplify or mitigate hazard exposure.

Underlying these physical drivers, socioeconomic and methodological factors further explain regional variation. Communities with limited infrastructure and governance capacity absorb shocks less effectively, as Brooks et al. (2005) have shown, and Ayodotun et al. (2019) document how poverty intensifies flood and drought impacts in West Africa. Assigning equal weights to all five hazards can obscure synergistic effects such as drought-driven wildfire amplification, a caveat raised by Jurgilevich et al. (2017). Moreover, uncertainties in climate-model projections and evolving socioeconomic trajectories necessitate flexible response frameworks (Sherbinin et al., 2019). Incorporating local coping practices illustrated by river-basin resilience studies in Tanzania can refine vulnerability estimates and support tailored adaptation strategies (Macharia et al., 2020).

2.3 Hotspots and critical impact zones

Identifying the most affected climate change hotspots is key to designing focused interventions. The Sahel, which stretches as a semi-arid belt from Senegal to Chad, endures severe disruptions from prolonged dry spells and erratic rainfall, jeopardizing agriculture, water resources, and food security. This region is increasingly troubled by these climatic stresses (Diffenbaugh and Giorgi, 2012), with tropical West Africa encompassing nations like Ghana, Nigeria, and Côte d'Ivoire experiencing pronounced risks to both agriculture and biodiversity (Müller et al., 2014). The convergence of these physical hazards with socio-economic challenges such as widespread poverty and limited adaptive capacity underscores an urgent need for region-specific responses (Turco et al., 2015; Fan et al., 2021). Climate models further predict that rising temperatures and altered precipitation

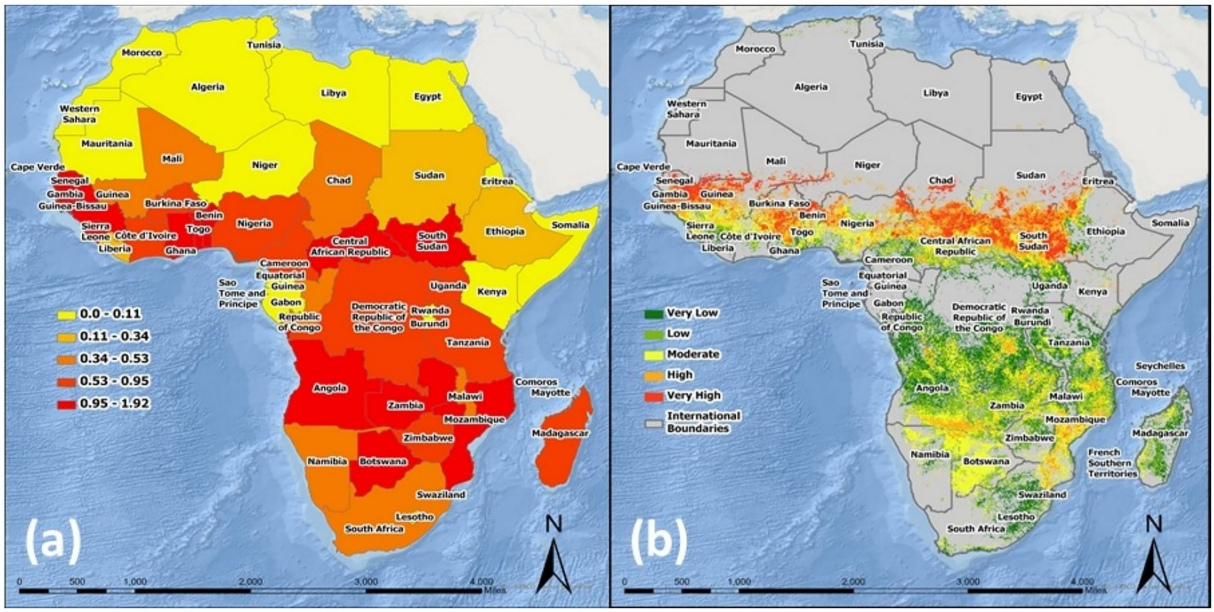


FIGURE 1
Vulnerability map across Africa based on climate extremes, **(a)** country-level, **(b)** sub-national level.

patterns may reduce yields of staple crops such as maize and sorghum by up to 20% by mid-century (Jantz et al., 2015). Increased variability is also expected to drive more frequent extreme events, such as droughts and floods, which disrupt agricultural cycles and further compromise food security for communities already grappling with production uncertainties (Omer et al., 2024; Schroth et al., 2016). Such trends have broader implications, undermining rural economies, public health, and community resilience, thereby necessitating robust, integrated climate adaptation measures in these vulnerable zones (Bezeng et al., 2017; Salamanca et al., 2023).

3 Impacts of climate change on key sectors

Climate change is fundamentally altering Africa's critical sectors, with sweeping impacts on agriculture, water resources, public health, and overall socioeconomic stability. Rising temperatures, erratic precipitation, and an increase in extreme weather events are eroding food security, disrupting water management systems, and worsening health and economic vulnerabilities. By bringing together evidence from these diverse yet interconnected areas, this section highlights the urgent need for comprehensive adaptation strategies that address the complex challenges facing African communities. Such integrated approaches are essential for charting a path toward resilient and sustainable development.

3.1 Agriculture and food security

Climate variability is negatively affecting agricultural production across Africa, especially in sub-Saharan regions, West, East, Central, and Southern Africa, where subsistence farming predominates. Rising temperatures and shifting precipitation patterns have already reduced yields of staple crops such as millet and sorghum, with projections suggesting potential crop losses of around 8% under future scenarios (Sultan et al., 2019). In West Africa, prolonged droughts and an increased frequency of extreme weather events disrupt planting and harvesting cycles, while excessive rainfall and long dry spells further trigger widespread crop failures and shrink the area suitable for farming (Aboua, 2020; Sultan et al., 2023).

In response to these escalating challenges, smallholder farmers are increasingly embracing a variety of adaptive strategies. Many are diversifying their crop portfolios by introducing drought-resistant and climate-resilient varieties capable of withstanding temperature extremes and unpredictable rainfall (Waha et al., 2018; Baya et al., 2019). Practices such as conservation agriculture and agroforestry are gaining momentum as effective approaches to sustain soil health and bolster resilience against climate variability (Tarchiani et al., 2018). Enhanced access to agrometeorological services also enables farmers to better synchronize their planting and harvesting schedules with reliable weather forecasts, while educational initiatives continue to empower them to implement these adaptive practices more effectively (Mechiche-Alami and Abdi, 2020; Umetsu and Miura, 2023).

The repercussions of these climate-induced disruptions extend beyond reduced crop yields to directly threaten food security across sub-Saharan Africa. As yields become increasingly volatile, agriculture-dependent households face higher risks of food shortages, and declining outputs drive food prices upward, exacerbating the hardships of impoverished families (Deryng et al., 2011; Parkes et al., 2015). Moreover, the interplay between climate change and demographic pressures may further intensify migration as communities seek improved living conditions (Defrance et al., 2020). Thus, addressing the impacts of climate change on agriculture is vital not only for sustaining production

TABLE 1 Climate extremes' impact on African regions.

Region	Climate extreme	Impact	Reference citations
Sahel	Droughts	Severe water scarcity, reduced agricultural productivity, food insecurity, and increased resource conflicts.	Wright et al. (2024), Badolo (2024)
West Africa	Floods	Displacement of communities, destruction of infrastructure, and increased incidence of waterborne diseases.	Wright et al. (2024), Nigatu et al. (2014)
East Africa	Droughts and Floods	Crop failures, livestock mortality, food and water shortages, displacement of communities.	Mthembu and Zwane (2017), Hummel et al. (2018)
Southern Africa	Heatwaves	Heat-related illnesses, reduced crop yields, increased energy demand for cooling, and wildfires.	Clarke and Berry (2012), Hummel et al. (2018)
Central Africa	Heavy Rainfall	Landslides, soil erosion, disruption of transportation networks, and flooding of urban areas.	Perez et al. (2022)
North Africa	Droughts	Water scarcity, desertification, reduced agricultural productivity, and migration.	Antwi-Agyei et al. (2017), Ebi and Barrio (2017)

levels but also for ensuring stable and accessible food systems. Facilitating the adoption of effective adaptation measures among smallholder farmers is key to safeguarding food security and enhancing overall resilience in a changing climate (Olabanji et al., 2020).

3.2 Water resources

Many African communities have long drawn on indigenous knowledge to manage water scarcity and optimize water use. Traditional practices, such as rainwater harvesting for seasonal capture, constructing small reservoirs, designing pervious surfaces to promote groundwater recharge, and building contour bunds to reduce runoff, demonstrate a profound understanding of local hydrology deeply connected to ecological rhythms and cultural calendars (Mganga et al., 2021; McNally et al., 2019). These time-honored methods have enabled communities to effectively adapt to shifting climate conditions and maintain sustainable water supplies in the absence of formal management systems.

However, despite the clear benefits of these indigenous approaches, modern policy frameworks often prioritize technical solutions over local expertise (Wallace and Gregory, 2002). Integrating indigenous wisdom with contemporary scientific methods can enhance adaptive capacity and lead to more efficient water use, as evidenced by studies showing higher resilience to climate variability when traditional practices are employed (Das et al., 2015; Ferrand and Cecunjanin, 2014). Numerous examples illustrate the effectiveness of these strategies: the Akwamu community in Ghana employs religious norms and ancestral conservation techniques to preserve water bodies (Osei, 2023), while in South Africa, practices like rainwater harvesting, terracing, and wetland management mitigate water scarcity amid erratic rainfall patterns (Sahani et al., 2025). Similarly, Zimbabwe's Ndau community blends cultural rituals with environmental wisdom (Tenson and Richard, 2014), and local governance in Northern Namibia draws on historical practices to facilitate resource distribution and build resilience (Hossain and Helao, 2008).

In response to escalating climate challenges, governments and non-governmental organizations across Africa are adopting a range of adaptation strategies within the water sector. Efforts include modernizing infrastructure, implementing water-saving technologies such as drip irrigation (Adonadaga et al., 2022), and establishing transboundary management frameworks to encourage regional collaboration (Rankoana, 2020). Concurrently, rising populations and rapid urbanization, projected to increase urbanization from about 40% to over 60% by 2050 and urban water demand by 50–80% over the next three decades, are further stressing freshwater supplies (Santos et al., 2017; He et al., 2021; Bojer, 2025). Additionally, climate variability decreases per capita water availability as resources are increasingly diverted to meet domestic, agricultural, and industrial needs, while intensified anthropogenic activities degrade water quality and burden treatment and supply systems (Gebrehiwot and Gebrewahid, 2016; Hasan et al., 2019). In this context, innovative adaptation strategies that blend traditional knowledge with modern technologies are essential for achieving sustainable water management and bolstering climate resilience (Nhamo et al., 2018). Table 1 offers an overview of how climate extremes affect various regions of Africa, providing detailed regional insight that enables stakeholders to develop targeted adaptation strategies to address each area's unique vulnerabilities and build greater resilience.

3.3 Health and socioeconomic impacts

Climate change is significantly compromising both public health and socioeconomic stability in Africa. Increased temperatures, altered precipitation patterns, and more frequent extreme weather events are intensifying health risks and disrupting livelihoods. This section examines the interdependent nature of these challenges, revealing how deteriorating health outcomes and economic instability mutually

TABLE 2 Health impacts due to climate change in Africa.

Health impact	Contributing climate factors	Examples and observations	Reference citations
Heat-related illnesses	Rising temperatures, heatwaves	Increased incidence of heat stress, heat exhaustion, and heat stroke among vulnerable populations.	Berry et al. (2018)
Respiratory conditions	Altered precipitation patterns, increased air pollution	Worsening of asthma and other respiratory diseases due to higher pollution levels and pollen distribution changes.	Clarke and Berry (2012)
Vector-borne diseases	Shifting climatic zones, increased humidity	Expanded range and transmission of diseases like malaria and dengue fever to previously unaffected areas.	Obradovich et al. (2017)
Mental health issues	Extreme weather events, displacement	Higher rates of anxiety, depression, and trauma among individuals exposed to climate-related disasters.	Stilita and Charlson (2024)
Waterborne diseases	Flooding, contaminated water sources	Increased incidence of cholera, typhoid, and other waterborne diseases following flooding and water contamination.	Nigatu et al. (2014), Perez et al. (2022)
Nutritional deficiencies	Declining agricultural productivity, food insecurity	Malnutrition and stunting are due to reduced crop yields and food shortages.	Ebi and Barrio (2017), Hummel et al. (2018)
Non-communicable diseases	Rising temperatures, altered lifestyle factors	Higher prevalence of conditions such as cardiovascular diseases is linked to heat stress and changes in physical activity.	Cardwell and Elliott (2013)

reinforce each other. It underscores the urgent need for integrated adaptation strategies to foster resilient communities across the continent.

3.3.1 Assessment of health vulnerabilities

Environmental shifts driven by climate change elevate public health risks by intensifying exposures in climate-stressed regions. Increasing temperatures, irregular precipitation, and recurrent extreme events contribute to a range of ailments, from heat-related illnesses and respiratory conditions to the accelerated spread of infectious diseases (Berry et al., 2018). Moreover, shifts in climatic zones are expanding the prevalence of vector-borne illnesses such as malaria and dengue fever, exposing populations that were previously at lower risk (Obradovich et al., 2017). Extreme weather events also precipitate mental health challenges, with affected individuals experiencing greater levels of anxiety and depression. Incorporating these diverse risk factors into public health assessments is crucial for directing effective adaptation strategies (Buse, 2018).

In Africa, the impact of climatic stressors on health is particularly pronounced. Vulnerable communities, especially internally displaced persons and refugees, face heightened mental health challenges, as evidenced by studies in regions like Somalia and Tanzania that report increased trauma and anxiety linked to forced migration (Stilita and Charlson, 2024; Sanni et al., 2022). Additionally, extreme events such as flooding not only lead to immediate physical injuries but also accelerate the spread of waterborne diseases, intensifying overall health risks. The World Health Organization has identified climate change as a major threat, with children, the elderly, and those with pre-existing conditions being especially susceptible (Nigatu et al., 2014).

Beyond direct health impacts, climate-induced stress on healthcare systems compromises access to quality care and contributes to higher morbidity and mortality rates related to climate-sensitive conditions (Cardwell and Elliott, 2013). It is essential to integrate localized health vulnerability insights into public health planning and response initiatives to build resilient systems (Cheng and Berry, 2013). Enhancing awareness and implementing targeted training for health professionals can help synchronize healthcare responses with adaptive strategies, bridging critical knowledge gaps (Berry et al., 2018; Andersen et al., 2021). Table 2 summarizes both the direct and indirect impacts of these climatic changes on African populations, providing a basis for developing informed and robust public health strategies.

3.3.2 Broader socioeconomic consequences

Climate change triggers wide-ranging socioeconomic impacts that affect nearly every facet of life. Unstable climatic conditions diminish agricultural productivity, thereby compromising food security and contributing to malnutrition and health disparities among vulnerable populations (Ebi and Barrio, 2017). In addition, the economic fallout, including increased healthcare costs, reduced productivity, and disrupted livelihoods, intensifies existing inequalities and deepens poverty. These conditions often spur climate-induced migration, as people abandon increasingly uninhabitable areas and place additional pressure on host communities (Eckelman and Sherman, 2016; Krasna et al., 2020).

In Africa, these repercussions are particularly severe. Low-income communities that depend on climate-sensitive sectors suffer notable declines in crop production, as rising temperatures and altered precipitation patterns reduce yields; for example, drought stress is expected to diminish common bean yields in southern Africa,

TABLE 3 Broader socioeconomic consequences of climate change on African regions.

Region	Socioeconomic consequence	Description	Reference citations
Sahel	Declining agricultural productivity	Reduced crop yields and livestock productivity due to prolonged droughts, leading to food insecurity.	Hummel et al. (2018), Ebi and Barrio (2017)
West Africa	Migration and displacement	Increased migration and displacement of populations due to flooding and loss of arable land.	Krasna et al. (2020), Wright et al. (2024)
East Africa	Economic losses	Economic losses from damaged infrastructure and reduced tourism due to extreme weather events.	Badolo (2024), Perez et al. (2022)
Southern Africa	Health impacts	Higher incidence of waterborne diseases and malnutrition due to disrupted water resources and food supply.	Nigatu et al. (2014), Perez et al. (2022)
Central Africa	Social strain and conflicts	Increased social strain and conflicts over diminishing natural resources such as water and arable land.	Ebi and Barrio (2017), Chersich and Wright (2019)
North Africa	Water scarcity	Severe water scarcity is affecting agriculture, domestic use, and industrial activities.	Antwi-Agyei et al. (2017), Zvobgo et al. (2022)
Sub-Saharan Africa	Poverty and inequality	Exacerbation of poverty and inequality due to economic disruptions and loss of livelihoods.	Eckelman and Sherman (2016), Hummel et al. (2018)

impacting both the available growing area and the nutritional quality of produce (Hummel et al., 2018). Reduced agricultural output drives food prices higher, which increases the risk of malnutrition among populations already burdened by economic hardship (Kirchhoff and Watson, 2019). Meanwhile, disruptions in water resources hinder agricultural irrigation and domestic supply, elevating the spread of waterborne diseases and further straining public health systems (Chersich and Wright, 2019; Perez et al., 2022).

Socioeconomic disparities further compound these challenges. Marginalized groups, particularly women and individuals with lower incomes, often lack the means to adapt effectively, while governance structures tasked with implementing adaptation measures are hampered by inadequate infrastructure, limited funding, and low political commitment (England et al., 2018; Quintana et al., 2024). Rapid urban expansion also challenges access to safe drinking water, intensifying the adverse effects of climate change in many regions (Zvobgo et al., 2022). Addressing these complex issues requires a cross-sectoral approach that weaves climate adaptation strategies into disaster risk reduction, food security, and public health policies, along with robust community engagement to ensure context-specific responses (Ford et al., 2014; Ekstrom et al., 2017). Table 3 summarizes the broader socioeconomic consequences of climate change across various African regions, providing essential insights for developing targeted strategies to mitigate adverse impacts on vulnerable communities.

4 Strategies for enhancing climate resilience

Addressing the multifaceted challenges of climate change demands holistic strategies that reinforce resilience across diverse sectors. This section examines an array of innovative adaptation approaches that blend indigenous wisdom, modern agricultural methods, and forward-thinking policy frameworks. By combining time-honored traditional practices with state-of-the-art technology and fostering active community participation, these strategies aim to build robust systems capable of withstanding climate-related adversities while promoting sustainable development throughout Africa.

4.1 Leveraging indigenous knowledge and community approaches

Figure 2 exemplifies the power of merging indigenous insights with climate-smart agricultural strategies to enhance community resilience while preserving cultural heritage. By integrating time-tested local methods with modern innovations, communities are empowered to more effectively mitigate and adapt to the impacts of climate change. This visual representation highlights key examples of both traditional and advanced practices, demonstrating how their complementary roles contribute to the development of sustainable, adaptive agricultural systems.

4.1.1 Role of indigenous knowledge in climate adaptation

Indigenous knowledge is a vital component of climate adaptation strategies, particularly in Africa, where local communities have developed profound interactions with their natural environments. For example, Egah et al. (2023) emphasize that indigenous knowledge systems enable communities to predict climate events effectively, thereby enhancing food security in agro-pastoral households. Traditional methods, such as rainwater harvesting, crop diversification, and the cultivation of drought-resistant indigenous species, have long been employed to manage water scarcity and support food security (Chanza and Musakwa, 2022). Furthermore, practices like agroecological techniques and the selective breeding of locally adapted crops highlight how context-specific adaptive strategies are developed to endure shifting climatic conditions (Egah et al., 2023). Such insights are crucial for anticipating and mitigating the adverse impacts of climate extremes, which increasingly threaten agricultural productivity in many regions.

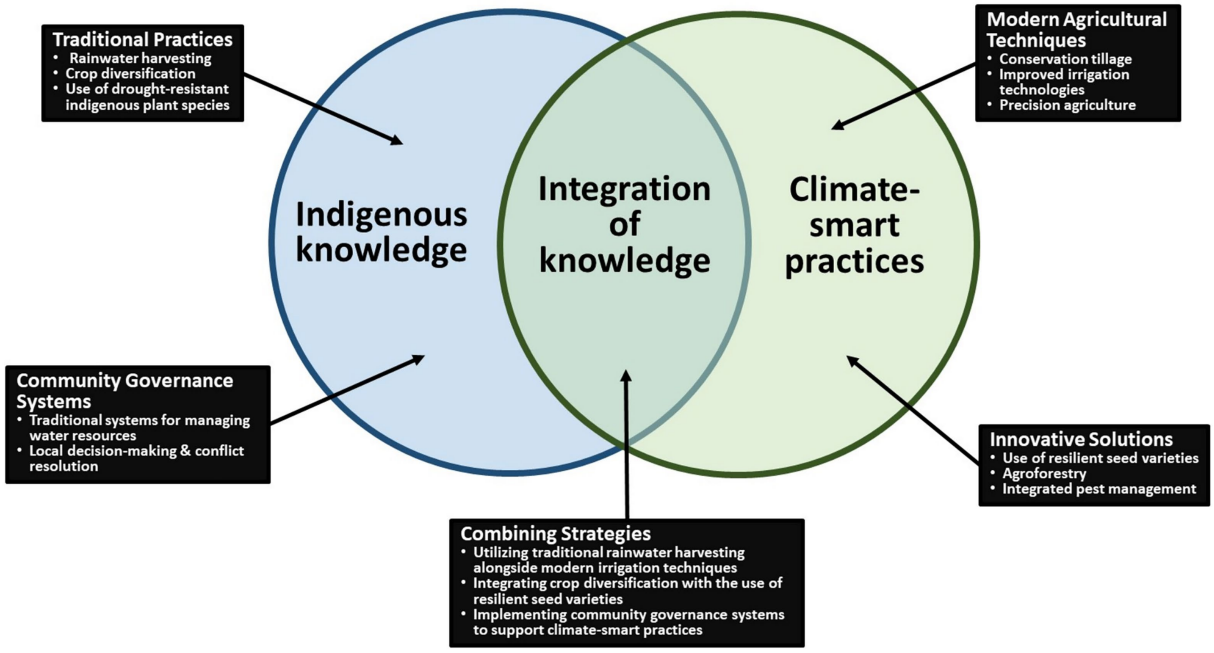


FIGURE 2
Indigenous knowledge and climate-smart practices.

Blending these time-tested practices with innovative scientific approaches not only reinforces the resilience of agricultural systems but also promotes local ownership of adaptation initiatives (Nesterova, 2020). Valuing indigenous knowledge, shaped by centuries of interaction with the local environment, ensures that adaptation measures are culturally relevant and effectively counter contemporary climate stresses (Acharibasam, 2022). Indigenous communities continually refine their agricultural techniques by closely monitoring environmental changes, thus actively managing climate risks (Datta, 2024). When combined with scientific research, these local insights lead to holistic strategies that empower communities to respond proactively to climate change, preserve cultural heritage, and strengthen social cohesion. Such integrative approaches ultimately enhance environmental stewardship, foster healthier ecosystems, and build more resilient food systems, contributing to broader climate resilience (Rahman and Alam, 2016; Smith, 2018; Fillmore and Singletary, 2021).

4.1.2 Case studies of community-based adaptation initiatives

Across Africa, numerous initiatives illustrate how blending indigenous knowledge with community-based adaptation measures can significantly boost resilience. In Kenya, for example, farmers have reintroduced traditional crop varieties that are naturally attuned to local climatic conditions, thereby enhancing food security and fostering sustainable agricultural practices (Korovulavula et al., 2019). Similarly, communities in southern Ethiopia have revived time-honored water management systems to effectively cope with drought, ensuring a reliable water supply for both agricultural and domestic needs (Agholor et al., 2023). These locally driven adaptations not only reinforce resilience but also strengthen community cohesion through empowered, decentralized decision-making.

Educational programs and participatory workshops further amplify these efforts by enabling communities to share experiences and collectively refine adaptive strategies. In rural Ghana, interactive workshops have provided a platform for farmers to exchange insights and develop adaptation measures that align traditional practices with evolving climate realities (Rankoana, 2020). Such initiatives underscore the importance of incorporating cultural values and indigenous knowledge into official adaptation plans, resulting in solutions that are both contextually relevant and sustainable (Rivero-Romero et al., 2016). An inclusive approach that values traditional practices has proven instrumental in fortifying community resilience against climate change (Scotti et al., 2023; Kamakaula, 2024).

Additional research further highlights the pivotal role of indigenous knowledge in climate adaptation. In North Benin, studies have shown that traditional forecasting methods are crucial for predicting climate events and safeguarding food security for agro-pastoral households (Egah et al., 2023). Likewise, Afar pastoralists in northeastern Ethiopia rely on ancestral weather forecasting techniques to inform critical decisions on livestock management and resource allocation amid climate variability (Balehegn et al., 2019). Table 4 presents a comprehensive overview of these case studies from diverse African regions, offering valuable insights into how indigenous knowledge and modern scientific methods can be integrated to craft scalable, resilient adaptation strategies.

4.2 Adoption of climate-smart agriculture

In the face of escalating climate challenges, the agricultural sector is increasingly turning to climate-smart agriculture (CSA) as a crucial strategy for promoting both sustainable productivity and resilience. CSA represents an integrated framework that fuses advanced

TABLE 4 Community-based adaptation initiatives in Africa.

Region	Adaptation initiative	Key strategies	Observed outcomes	Reference citations
Kenya	Use of indigenous crop varieties	Reverting to traditional seeds resilient to local climate conditions.	Improved food security and sustainability.	Korovulavula et al. (2019)
Southern Ethiopia	Traditional water resource management	Establishing systems for managing water resources during droughts.	Ensured water availability for agricultural and domestic use.	Agholor et al. (2023)
Rural Ghana	Participatory workshops for climate adaptation	Empowering farmers through knowledge sharing and collective adaptive strategies.	Improved agricultural practices align with the changing climate.	Rankoana (2020)
North Benin	Indigenous knowledge for climate prediction	Using traditional knowledge to predict climate events and safeguard food security.	Enhanced decision-making and resource management.	Egah et al. (2023)
Northeastern Ethiopia	Indigenous weather forecasting by Afar Pastoralists	Utilizing traditional weather forecasting for informed decisions on livestock management.	Better preparedness and resilience to climate variability.	Balehegn et al. (2019)

technological innovations with longstanding indigenous practices and community-led initiatives, enhancing resource management, boosting crop yields, and mitigating greenhouse gas emissions. By combining cutting-edge techniques with local wisdom, CSA offers a comprehensive solution that equips smallholder farmers to effectively adapt to climate variability while securing long-term food security. In this section, we examine the core practices, technological developments, and integrative methodologies that are driving the successful adoption of climate-smart agriculture across Africa.

4.2.1 Overview of climate-smart practices and technologies

Climate-smart agriculture (CSA) is a holistic framework intended to boost productivity, enhance climate resilience, and reduce greenhouse gas emissions (Scherer and Verburg, 2017). It merges a range of practices and technologies specifically tailored to local environmental, agricultural, and socio-economic conditions. For example, CSA often incorporates drought-resistant crop varieties, agroforestry, crop rotation, conservation tillage, and advanced irrigation systems such as drip and sprinkler technologies (Anuga et al., 2022; Nandini et al., 2023). These methods optimize resource use, improve soil quality, and facilitate carbon sequestration, thereby supporting sustainable land management.

In Africa, CSA has become essential for smallholder farmers, who form the backbone of the agricultural sector, as it helps manage climate impacts while increasing productivity and ensuring food security (Khoza et al., 2021; Gugissa et al., 2022). By emphasizing improved soil management, diversified crop production, and resilient seed varieties, farmers are better equipped to endure climate stress. Nonetheless, the widespread adoption of CSA faces challenges, with limited access to resources, technological expertise, and financial support remaining significant obstacles that require coordinated responses from governments, NGOs, and local communities (Clay and Zimmerer, 2020).

Moreover, noteworthy CSA innovations include organic farming practices that reduce the reliance on synthetic fertilizers and pesticides, thus mitigating the environmental footprint of agriculture (Sanogo et al., 2017). Techniques such as rainwater harvesting and precision agriculture utilize data to minimize waste and maximize yields under variable climatic conditions. The integration of these advanced strategies with traditional practices supports sustained agricultural output, lowers farming systems' vulnerability to climate variability, and ultimately enhances food security and the livelihoods of smallholder farmers (Fiawoo et al., 2024).

4.2.2 Integrative approaches to improve productivity and sustainability

Enhancing agricultural productivity and sustainability requires a cohesive strategy that combines technological innovations, traditional knowledge, and active community engagement (Teklewold et al., 2018). By fostering participatory research methods and implementing educational initiatives, farmers are enabled to tailor CSA practices to their specific local conditions, thereby boosting acceptance and effective implementation (Mirzabaev, 2017). Critical to this process is the role of local leadership and the willingness of farmers to adopt practices that align with their cultural values and longstanding agricultural traditions (Sanogo et al., 2017).

Creating synergies among agricultural policies, climate resilience strategies, and economic incentives is equally vital. Programs that offer improved access to credit, sophisticated training, and practical resources for climate-smart technologies can drive broader adoption of these systems (Amare and Gacheno, 2021). Additionally, collaboration among government entities, NGOs, and local communities fosters a holistic approach to resilient agricultural development by integrating diverse perspectives and expertise to address climate change challenges (Nkonya et al., 2017). For example, agroecological practices, integrating modern techniques with traditional methods, have been shown to enhance biodiversity, improve water retention, and boost soil fertility, all of which are essential to sustaining robust food systems (Kifle et al., 2020). As the impacts of climate change become more severe, embedding these integrative approaches within CSA is key to building agricultural systems that are resilient and capable of withstanding future climatic challenges.

4.3 Policy and governance frameworks

Building climate resilience in Africa calls for strong adaptation policies supported by effective local governance and participatory mechanisms. By basing policies on local conditions and engaging stakeholders throughout the adaptation process, governments can foster environments that support sustainable development and robust risk management.

4.3.1 Need for robust climate change adaptation policies

Addressing Africa's escalating climate challenges requires strong adaptation policies that provide a clear framework for governments at every level, national, regional, and local, to design and implement strategies that respond to their communities' unique needs (Chersich and Wright, 2019). Grounded in scientific research and adapted to local realities, these policies ensure that measures are both practical and context-specific. For instance, South Africa's National Climate Change Response Policy, which effectively integrates climate health considerations into local government plans, serves as an inspiring model for other nations (Quintana et al., 2024). Furthermore, aligning adaptation policies with existing sectoral strategies in areas such as agriculture, water, and health, as well as ensuring that local governments possess the necessary capacity to execute these plans, is critical to their overall success (Antwi-Agyei et al., 2017).

To be truly effective, adaptation policies must also prioritize inclusiveness by actively engaging marginalized and vulnerable communities in the decision-making process (Ranabhat et al., 2018). Climate governance frameworks that emphasize transparency, accountability, and collaboration among diverse stakeholders are essential for fostering sustainable practices and building robust community resilience (Chersich and Wright, 2019). Ultimately, well-crafted and comprehensive climate adaptation policies empower governments to proactively mitigate climate impacts, enabling communities to not only survive but thrive in the face of environmental challenges.

4.3.2 Mechanisms for effective local governance and stakeholder participation

Effective climate adaptation relies on strong local governance paired with active stakeholder participation. Local governments, which possess an intimate understanding of community vulnerabilities, are crucial for transforming climate policies into actionable measures (Pasquini et al., 2014). Establishing multi-stakeholder platforms that bring together government representatives, community leaders, NGOs, and citizens fosters ongoing dialogue and ensures that adaptation initiatives are finely tuned to local conditions and diverse perspectives (Twinomuhangi et al., 2019).

Enhancing the capacity of local authorities through proper resource allocation and targeted capacity building is equally important for the success of adaptation measures. Equipping decision-makers with data-driven insights, supported by accurate climate information and forecasting, greatly improves their ability to respond proactively (Huh et al., 2017). Additionally, integrating indigenous knowledge into formal governance structures enhances local responsiveness and adaptability (Crane et al., 2011). Maintaining robust communication channels between governments and communities is vital for shared understanding of climate risks and the appropriate adaptation measures. Public awareness campaigns that underline climate impacts and adaptive strategies help foster community engagement and cultivate a sense of ownership over adaptation efforts (Harris and Howe, 2023). When stakeholders are well-informed, trained, and actively involved in both planning and implementation, communities build the agency necessary to enhance their resilience against climate change challenges (Quintana et al., 2024).

5 Future directions in building Africa's climate resilience

As Africa grapples with mounting climate impacts, it is imperative to devise forward-thinking strategies that not only address today's challenges but also establish the foundation for long-term resilience and sustainability. This section outlines future directions designed to strengthen climate adaptive capacity throughout the continent. By enhancing existing adaptation frameworks, filling crucial knowledge gaps, and prioritizing strategic investments, African nations can better anticipate and manage the complex spectrum of climate challenges ahead. Moving forward, collaborative efforts, innovative approaches, and robust policy development will be key to building a resilient and sustainable future for all communities across Africa.

5.1 Building on existing frameworks for climate resilience

As climate change impacts in Africa intensify, it is imperative to strengthen and refine existing resilience frameworks to support effective adaptation strategies. A key initiative in this effort is the African Climate Resilience Acceleration (ACRA) roadmap, which serves as an essential decision-support tool for policymakers and local governments (Badolo, 2024). This roadmap employs a comprehensive framework that incorporates methodologies to assess climate vulnerabilities, identify context-specific solutions, and prioritize actions that build adaptive capacity. By leveraging the ACRA roadmap, governments can develop strategies that are coherent with local priorities and foster sustainable development amid increasing climate variability.

Beyond its tailored solutions, the ACRA roadmap actively promotes collaboration among diverse stakeholders, including local communities, NGOs, and the private sector, thereby creating a united front against climate impacts (Gemenne and Blocher, 2017). Drawing on the perspectives of these varied actors enables the development of innovative interventions across critical sectors such as agriculture, health, and water management (Keane et al., 2018). The framework also emphasizes the need for robust monitoring and evaluation systems to track progress and guide ongoing adaptations, fostering a culture of continuous learning and improvement (Sultan et al., 2019).

Enhancing climate resilience further requires integrated, multi-sectoral approaches where climate-smart agriculture, sustainable water management, and effective public health policies converge to create synergistic pathways for adaptation (Wang et al., 2024; Roy et al., 2022). Joint initiatives that facilitate resource sharing and expertise exchange align local adaptation efforts with broader development objectives like the Sustainable Development Goals (Mayer et al., 2023). Empowering local governance enables authorities

to tailor measures to specific community landscapes, while participatory governance models engage citizens and reinforce socio-ecological resilience (Badolo, 2024). Figure 3 illustrates these integrative approaches, highlighting how uniting sectors such as agriculture, water management, and public health is essential for building long-term climate resilience across Africa.

5.2 Addressing knowledge gaps

Addressing knowledge gaps is critical for fostering climate resilience across Africa, as socio-economic conditions, cultural practices, and environmental factors jointly shape how communities perceive and respond to climate risks. Historically, analyses have prioritized ecological processes over socio-economic dimensions, leaving a divide between natural-science insights and human-centered adaptation needs (Hulme, 2018). Bridging these divides requires integrated frameworks that unite ecological, social, and cultural expertise to inform holistic strategies, especially in contexts where resources for interdisciplinary research are limited (Orr et al., 2022; Chausson et al., 2020).

One of the most pressing gaps exists among smallholder farmers, many of whom acknowledge climate change but lack detailed understanding of its causes, specific local threats, and viable adaptation options (Ubisi et al., 2017). A lack of accurate weather forecasts and reliable meteorological infrastructure further undermines their decision-making on crop management, risk mitigation, and resource allocation (Ayanlade et al., 2017; Gebre et al., 2023). To address these shortfalls, educational initiatives must blend scientific research with indigenous knowledge systems, using locally adapted technologies such as traditional water-harvesting techniques paired with modern sensors to empower farmers and deepen community-wide comprehension of climate-smart practices (Kom et al., 2020; Sibiya et al., 2022).

Socio-political dynamics also influence the uptake of adaptation measures, as communities that perceive climate change as human-driven tend to engage more readily with resilience initiatives (González and Sánchez, 2022). In contrast, skepticism or indifference can stall local projects unless communication strategies are tailored to resonate with lived experiences and values (Ziervogel et al., 2014). At the policy level, insufficient climate literacy among government officials limits the development of comprehensive adaptation frameworks, and narrowly economic policies risk exacerbating vulnerabilities by sidelining environmental sustainability (Onyeneke et al., 2021; Wako et al., 2017). Establishing knowledge-sharing platforms that convene researchers, policymakers, and community representatives is essential to ensure that diverse perspectives guide robust, context-sensitive policy design (Joseph et al., 2021).

The availability and quality of climate data remain foundational to informed adaptation planning. Investments in regional meteorological networks and data-management systems can enhance forecast accuracy and enable proactive responses to extreme events (Faiyetole and Adesina, 2017). Integrating technological innovations such as drought-tolerant seed varieties, precision irrigation systems, and sustainable land-management practices with capacity-building programs ensures that new tools are effectively adopted and maintained (Cairns et al., 2013; Ampadu et al., 2018). By advancing data infrastructure, educational outreach, and interdisciplinary collaboration, Africa can close critical knowledge gaps and build a resilient foundation for sustainable livelihoods in the face of climate change. Table 5 details a concise summary of Section 5.2, outlining the

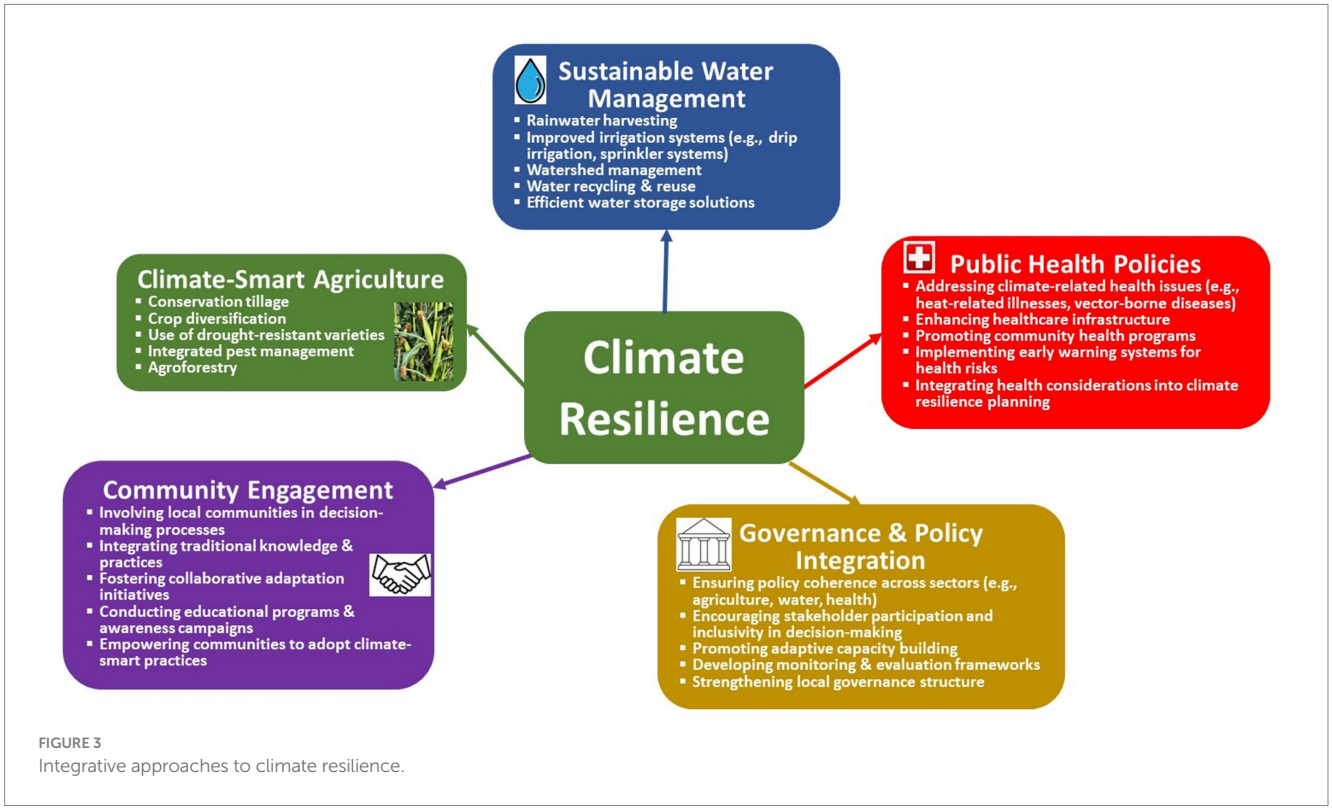


FIGURE 3
Integrative approaches to climate resilience.

TABLE 5 Knowledge gaps, implications, and proposed actions for building Africa's climate resilience.

Theme	Challenges/Details	Proposed actions	References
Integrating natural and social sciences	Historical emphasis on ecological processes over socio-economic impacts, limiting holistic adaptation frameworks	Establish interdisciplinary teams and co-created research agendas bridging environmental and human dimensions	Chausson et al. (2020), Hulme (2018), Orr et al. (2022), Turner et al. (2022)
Farmer understanding of climate	Limited awareness of specific local climate threats, causes, and adaptation options; inadequate meteorological data	Blend scientific research with indigenous knowledge; deploy locally adapted technologies; strengthen data systems	Ayanlade et al. (2017), Gebre et al. (2023), Kom et al. (2020), Sibiya et al. (2022), Ubisi et al. (2017)
Socio-political dynamics and policy literacy	Skepticism or indifference hinders uptake of adaptive practices; policymakers often lack climate literacy	Tailor communication strategies to community beliefs; create knowledge-sharing platforms for policymakers and stakeholders	González and Sánchez (2022), Joseph et al. (2021), Onyeneke et al. (2021), Wako et al. (2017), Ziervogel et al. (2014)
Data availability and technological integration	Inadequate meteorological infrastructure yields unreliable forecasts; risk of low adoption of innovations	Invest in regional climate networks and data management; integrate drought-tolerant seeds, precision irrigation, and land-management training	Ampadu et al. (2018), Cairns et al. (2013), Faiyetole and Adesina (2017)

main knowledge gaps, their implications, proposed actions, and key citations.

5.3 Innovative financing for climate projects

Securing adequate financial support for climate change adaptation is vital for African nations to address the multifaceted impacts of a shifting climate. Research by Betzold and Weiler (2017) reveals a significant gap between current financial resources and the investments required for effective adaptation, with particularly severe shortfalls in the continent's most vulnerable regions. As climate risks escalate, governments must prioritize funding that not only mitigates hazards but also enhances community resilience and promotes climate-smart practices. Climate-smart agriculture represents a critical approach to addressing agricultural development amid climate adversity, facilitating adaptations such as sustainable land and water management, which directly contribute to food security while minimizing greenhouse gas emissions (Abegunde et al., 2019; Kurgat et al., 2020). This backing can be sourced from bilateral and multilateral aid, domestic budgets, and innovative mechanisms such as the Green Climate Fund (Berrang-Ford et al., 2014), ensuring that under-resourced communities whose capacities to cope with climate impacts are already stretched receive the support they need (Moser et al., 2019).

Innovative financial instruments such as green bonds, climate risk insurance, and blended finance offer pathways to mobilize public and private capital for adaptation and mitigation. Cutter et al. (2003) emphasize that these tools enable risk-sharing arrangements that lower investment barriers, while Ayodotun et al. (2019) document how green bonds have successfully financed renewable energy projects across Africa, bolstering local economies and advancing climate goals. Public-private partnerships further deepen private-sector engagement. Brooks et al. (2005) demonstrate the effectiveness of PPPs in delivering resilient infrastructure such as flood-resistant water-management systems. Meanwhile, public and quasi-public finance institutions structure co-funding arrangements that de-risk investments and leverage indigenous knowledge, as Fry et al. (2024) illustrate through partnerships with established local organizations.

Despite this promise, persistent governance bottlenecks, capacity constraints, and inequitable fund distribution hamper co-funding mechanisms at the local level. Cabannes (2021) shows that weak institutional frameworks can stall participatory budgeting initiatives, skewing resources away from the most vulnerable. Studies underscore that the countries facing the highest climate risks often receive insufficient support (Betzold and Weiler, 2017; Moser et al., 2019), underscoring the urgent need to recalibrate funding mechanisms. Aligning investment flows with detailed vulnerability assessments enables targeted financial assistance, supporting local government initiatives, empirical research, and capacity-building programs that empower communities to manage climate impacts effectively (Adisa et al., 2024; Sarfo-Adu and Kokofu, 2023; Stender et al., 2019).

Embedding these innovative financing tools within collaborative governance models amplifies their impact. Bosma and Hein (2023) emphasize that effective adaptation and conservation investment strategies can only materialize through the integration of various stakeholders in the governance processes. Advanced technologies such as remote sensing, high-resolution climate analytics, and early-warning systems further lower costs and risks, providing actionable insights for resource allocation (Sherbinin et al., 2019). Participatory action research, as documented by Egah et al. (2023), ensures that these financial mechanisms reflect community-identified needs and leverage indigenous knowledge, creating a resilient, climate-smart future for Africa. Table 6 presents a concise summary of Section 5.3, highlighting the main themes, key details, and supporting references for innovative financing.

6 Conclusion

Africa stands at a pivotal juncture: climate projections now signal a continent-wide temperature increase of at least 1.5 °C, ranging from 1.15 to 1.50 °C in the south and 1.05 to 1.50 °C in the east, accompanied

TABLE 6 Overview of key themes, detailed approaches, and supporting references for innovative financing mechanisms.

Theme	Details	References
Funding gap and priorities	Africa needs US $293 bn - US $2.5 tn by 2030; diverse funding sources required to support resilience and smart practices	Betzold and Weiler (2017), Abegunde et al. (2019), Berrang-Ford et al. (2014), Kurgat et al. (2020), Moser et al. (2019)
Innovative financial instruments	Green bonds; climate insurance; blended finance offer risk sharing and mobilize private and public capital	Cutter et al. (2003), Ayodotun et al. (2019), Brooks et al. (2005), Fry et al. (2024)
Local governance challenges	Governance bottlenecks, capacity constraints, and inequitable distribution impede co-funding mechanisms	Adisa et al. (2024), Cabannes (2021), Sarfo-Adu and Kokofu (2023), Stender et al. (2019), Moser et al. (2019)
Collaborative governance and technology	Multistakeholder frameworks, remote sensing, climate analytics, and participatory research drive adaptive finance	Bosma and Hein (2023), Sherbinin et al. (2019), Egah et al. (2023)

by more intense heatwaves, cyclones, floods, and droughts. These oscillating extremes devastate rain-fed agriculture, erode livelihoods, and inflict massive losses in property, food production, and livestock. Semi-arid lowlands are especially vulnerable, undermining irrigation initiatives and exacerbating chronic water scarcity, while persistent warming intensifies pest and disease outbreaks that threaten to overwhelm coping capacities. Health systems buckle under new burdens of vector-borne and heat-related illnesses, coastal settlements face rising seas, and energy infrastructures strain under hotter, drier conditions. With up to 70 percent of the population reliant on rain-fed farming and adaptation finance falling short by nearly $486 billion, no nation can manage these compounded risks alone.

To build resilience, Africa must establish a robust, continent-wide climate-risk management architecture that continuously monitors hazards, forecasts emerging threats, and directs resources where they are needed most. This includes creating a pan-African Climate Resilience Observatory integrating satellite data, ground sensors, and community reporting; scaling climate-smart agriculture through drought-resistant seeds, efficient irrigation, and watershed restoration; and mobilizing innovative financing such as green bonds, climate funds, and debt-for-nature swaps, to close the adaptation financing gap. Strengthening governance and institutional capacity at national and subnational levels will ensure that policies remain adaptive as socio-economic and environmental conditions evolve.

Equally critical is forging an equitable global response that couples deep, early emissions reductions with technology transfer and safeguards against long-term risks. Aligning national commitments with the Paris Agreement's equity frameworks will protect Article 2's goal of limiting warming to well below 2 °C. Africa's resilience agenda must be underpinned by collaborative research, Indigenous knowledge integration, and regional cooperation among policymakers, scientists, local communities, and the private sector. Only through this holistic, multi-stakeholder approach can Africa transform the threats of climate change into opportunities for sustainable development and lasting innovation.

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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/fclim.2025.1619799/full#supplementary-material

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Framework for assessing the climate vulnerability of unpaved roads in Sierra Leone

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Introduction: Unpaved roads make up 80% of the global road network and 90% in developing countries. In Sierra Leone—one of the world's most climate-vulnerable nations—secondary unpaved roads account for 96% of the core network, serving as vital links for rural access, markets, and social inclusion. Yet, no structured framework currently guides the management of climate risks to these roads.

Methods: This study reviewed international climate risk and vulnerability assessment frameworks and identified their limited applicability in resource-constrained contexts due to heavy data demands, proprietary software, and high computing requirements. To address this gap, a five-phase, context-specific framework was developed, adapted from the IPCC vulnerability model. The framework employs cost-effective, open-source tech tools (QGIS, QField, PostGIS, cloud storage, and Microsoft Power BI) and integrates index-based, spatial, and stakeholder-driven approaches to generate composite indicators of road condition deficiency, maintenance efficacy, and roads' criticality.

Results: Application of the framework in Sierra Leone demonstrated its ability to identify climate-vulnerable unpaved road segments and highlight priority areas for adaptation. The framework proved practical under local data and institutional constraints, avoiding reliance on costly proprietary tools or high-end computing infrastructure.

Discussion: Nationally, the framework offers the first structured approach for integrating climate resilience into road management in Sierra Leone, supporting the National Roads Agency. Globally, it contributes a transferable, resource-efficient, and community-driven methodology for embedding climate adaptation into transport planning across the Global South. It aligned with national and international policies (Sierra Leone National Adaptation Plan (NAP), Sierra Leone Nationally Determined Contributions (NDC), UN Sustainable Development Goas (SDGs 9, 11 and 13).

KEYWORDS

unpaved roads, climate vulnerability, Sierra Leone, framework development, open-source tools, vulnerability assessment, road infrastructure resilience, sustainability

1 Introduction

Over the past four decades, sub-Saharan Africa has experienced more than 1,500 weather-related disasters [Emergency Events Database (EM-DAT), 2023], which have significantly affected its economy and rural livelihoods. Sierra Leone's tropical climate, characterized by alternating dry and wet seasons, exposes communities to a range of climate-related hazards

(World Bank, 2018a). The country's diverse geography increases the complexity of identifying road vulnerability, with each terrain posing unique challenges under climate stressors. This susceptibility is intensified by the increasing frequency of extreme weather events, such as floods, landslides, droughts, heatwaves, sea-level rise, and storm surges, combined with widespread dependence on natural resources. These factors collectively threaten critical infrastructure, especially road networks (World Bank, 2018b). Climate-related disasters are increasingly damaging road infrastructure through washouts, erosion, and structural failures, resulting in accidents, traffic disruptions, economic losses, and escalating maintenance costs. These impacts underscore the urgent need for vulnerability assessments to support climate-resilient adaptation and mitigation strategies.

Road transport is the dominant mode of transportation in Sierra Leoneaccounting for over 95% of inland passenger and freight movement, and it plays a crucial role in national development, particularly since the railway system was discontinued between 1970 and 1979 (Logistics Cluster, 2019). The country's 11,300 km road network includes primary (Grade A), secondary (Grade B), and feeder roads (Grade F). Of the 4,044 km core road network (CRN), only 40% is paved, while more than 96% of the remaining network consists of unpaved secondary roads. This imbalance presents significant challenges for road managers, particularly under the combined pressures of climate change, limited data, economic constraints, and climate expertise shortages (United Nations Development Programme, 2021; Nelson et al., 2019).

Given this context, unpaved roads, which account for more than 80% of the global road network (Ngezahayo et al., 2019), are particularly vulnerable to climate-induced damage due to their limited resilience and maintenance. In Sierra Leone, the absence of practical, locally adapted vulnerability assessment tools further exacerbates the problem. Despite their importance, these roads are often overlooked in structured climate risk evaluations, thus revealing a critical research gap in climate-resilient infrastructure planning. This paper addresses that gap by (i) reviewing existing frameworks for climate risk and vulnerability assessment; (ii) proposing a context-specific, cost-effective methodology informed by historical and projected climate data; and (iii) demonstrating the framework's applicability in identifying unpaved road segments most at risk from climate change. The findings aim to support data-driven planning and decision-making for sustainable road infrastructure management in Sierra Leone.

1.1 Reader's guide

his paper presents the development and application of a framework for assessing the vulnerability of unpaved roads to climate change in Sierra Leone. Section 1 introduces the study. Section 2 outlines the materials and methods, covering the study area, unpaved road context, data collection and analysis, indicator selection, climate hazards, and the vulnerability assessment framework. Section 3 provides a methodological overview and literature review, including climate risk assessment approaches, vulnerability levels, sensitivity, and exposure of unpaved roads. Section 4 applies the framework through case studies, highlighting its relevance to road agencies. Section 5 presents results from historical weather events, 30-year climate data, and exposure analysis. Section 6 discusses the findings, while Section 7 concludes with practical and policy implications, as well as the study's strengths and limitations. The final sections cover acknowledgements, author contributions, declaration of interests, and funding information.

2 Materials and methods

2.1 Study area

This study focuses on Sierra Leone, located on the west coast of Africa and characterized by a monsoon climate. The country is bordered by Guinea to the north and east, Liberia to the south, and the Atlantic Ocean to the west. It comprises four main geographic zones: interior plains, plateau and mountain regions, coastal marshes, and the Sierra Leone Peninsula [Comité Permanent Inter-états de Lutte contre la Sécheresse dans le Sahel (CILSS), 2016]. The coastal marsh region extends 320 km along the Atlantic Ocean, spanning 8 to 40 km in width, and is prone to flooding due to its sandy and clayey soils (USAID, 2016). The Sierra Leone Peninsula, which includes the capital city Freetown, features a forested mountain range that peaks at 880 m at Picket Hill. Inland, the interior plains encompass the seasonally flooded "Bolilands" in the north and the southern lowlands, characterized by rolling forested terrain and occasional hills exceeding 300 m in elevation (USAID, 2016). Figure 1 presents a map of Sierra Leone and highlights the key road networks, regions, and districts essential for conducting climate risk assessments.

Sierra Leone's tropical climate, characterized by a rainy season from May to September and a dry season from October to April, has increasingly contributed to weather-related disasters in recent years. Coastal and low-lying roads are particularly vulnerable to deterioration from intense rainfall, particularly in areas along the coast. In contrast, inland regions such as the Peninsula Mountains receive significantly higher annual rainfall (over 5,000 mm) than the north-eastern region (approximately 2,000 mm), which poses different but equally challenging conditions for road resilience (Kamara et al., 2025). To ensure the long-term sustainability of the road infrastructure, climate resilience assessments should prioritize drainage capacity, material durability, and adaptive maintenance strategies.

2.2 Description of unpaved secondary roads in Sierra Leone

This section details the infrastructure's sector, subsector, technical attributes, connectivity, and interactions with other infrastructure components, as required by a vulnerability assessment framework (Zebisch et al., 2021; Zlateva and Hadjitodorov, 2022). Such information supports a clearer understanding of the unpaved secondary road's functionality and its potential susceptibility to climate change impacts (Zebisch et al., 2021; Zlateva and Hadjitodorov, 2022). The Sierra Leone Roads Authority (SLRA) is responsible for managing national roads, while the Ministry of Transport and Aviation (MoTA) provides the policy and regulatory framework for transport governance and road safety. Furthermore, the Ministry of Works and Public Assets (MOWPA) oversees policy formulation and implementation for the

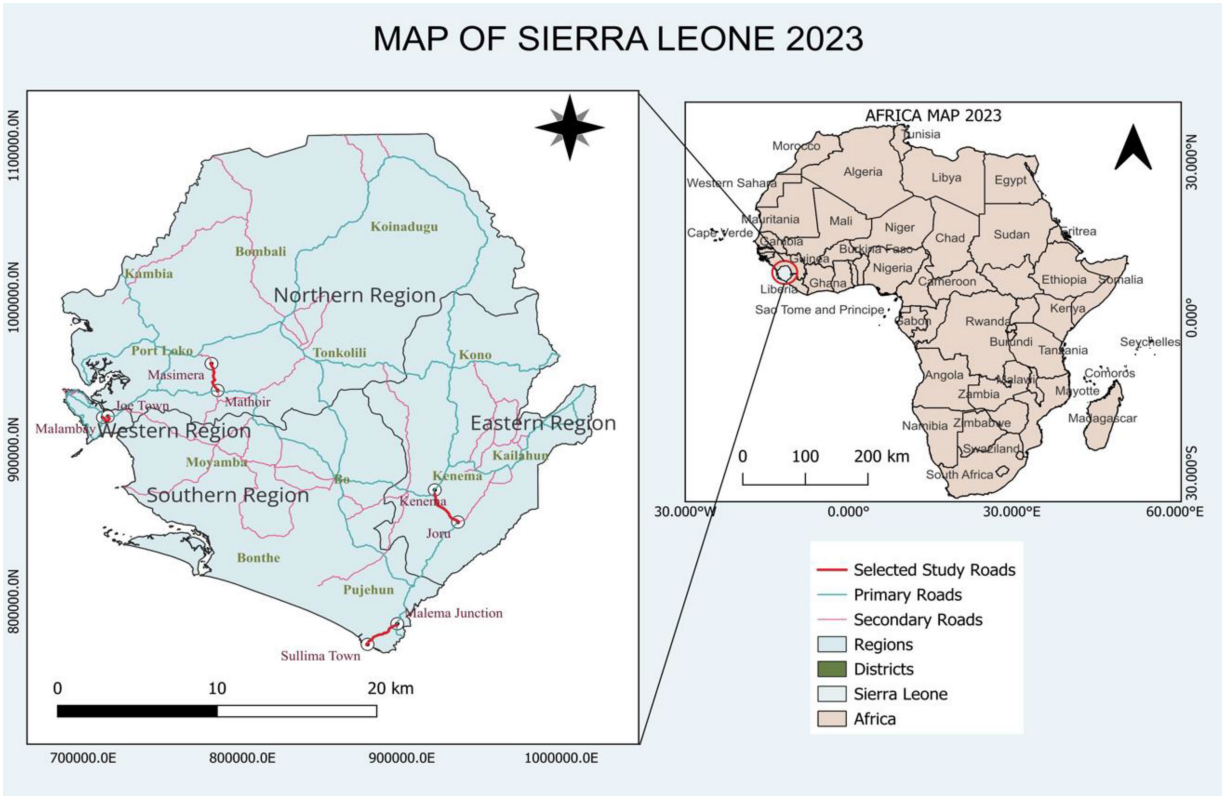


FIGURE 1
Map of Sierra Leone.

road and public asset sectors, including infrastructure construction, rehabilitation, and maintenance (Logistics Cluster, 2019).

According to the Sierra Leone Roads Authority (SLRA) road network classification, secondary roads constitute the second tier of the national road network (Padrosa, 2009). They connect district centers, towns, villages, and areas of tourism or agriculture (Bech Padrosa, 2009; Logistics Cluster, 2019). These roads serve as regional arteries that link production and distribution centers, while also functioning as intermediate connectors between primary (Class A) roads and feeder (Class F) roads. They facilitate a considerable volume of medium- and long-distance travel (Bech Padrosa, 2009; Logistics Cluster, 2019). Traffic along these roads typically comprised both through traffic (long-distance travel) and local traffic with origins or destinations nearby [Bech Padrosa, 2009; Research for Community Access Partnership (ReCAP), 2019]. Secondary roads facilitate the movement of passengers and freight by balancing mobility and access. However, conflicting movements such as intersections that require vehicles to slow down or stop may occur (Bech Padrosa, 2009; Logistics Cluster, 2019). Due to inadequate funding, these roads receive limited engineering and maintenance attention, despite their critical socioeconomic role in providing access to high-population centers and supporting economic activities. As a result, they face numerous challenges, which are further exacerbated by extreme weather events. These include frequent washouts, severe erosion, traffic disruptions, increased maintenance costs, fatalities during adverse weather, excessive dust in the dry season, and impassability during the rainy season [Research for Community Access Partnership (ReCAP), 2019].

2.3 Geographical context of unpaved secondary road locations

This section outlines the region's distinct geographic characteristics, including topography, land use, and climate patterns that may influence the infrastructure's susceptibility to climate-related hazards. Such contextual understanding informs the adaptation of the proposed framework to address the specific challenges and risks faced by infrastructure in the area, thereby enhancing the precision and relevance of the vulnerability assessment framework (Fleming et al., 2023). Geologically, Sierra Leone consists of the Liberian granite-greenstone terrain and the Kasila Group mobile belt, with diverse soil types such as sandy clay and loam. The country's dense drainage network, fed by rivers originating in the Fouta Djallon highlands of Guinea, presents significant challenges. Major rivers, including the Great Scarcies, Rokel, and Mano, traverse the national landscape.

Over the past four decades, Sierra Leone has experienced more than 110 weather-related disasters, indicating a concerning climatic trend (Delforge et al., 2023). Analysis on key climate variables, such as rainfall, temperature, wind speed, and relative humidity, revealed consistent upward trends over the past three decades. Furthermore, a near-term point forecast generated using a statistical autoregressive integrated moving average (ARIMA) time series model projected a continued increase in climate change and variability in the coming decades. These findings underscore the importance of evaluating the implications of key climate variables for unpaved secondary roads. Given that erosion is the primary impact factor for unpaved roads (Paige-Green and Verhaeghe, 2018) and considering the region's relief features and geomorphological, hydrological, and climatological

conditions, as well as historical data on natural disasters and recent extreme events, unpaved secondary roads are likely to be increasingly vulnerable to the adverse effects of climate change and variability. Accordingly, the implementation of the proposed framework is of vital importance for mitigating these impacts.

2.4 Data collection and analysis architecture for road vulnerability assessment

This section presents the data collection and analysis architecture developed to assess the vulnerability of unpaved secondary roads in Sierra Leone. The architecture was designed in response to persistent challenges such as data scarcity, limited technical capacity, high proprietary software costs, and infrastructural and financial constraints. It aims to provide a cost-effective, open-source, and practically replicable system that can be integrated into Sierra Leone's national road management framework. The architecture utilizes a combination of open-source geospatial tools, including QGIS, QField Mobile App, PostGIS, and QFieldCloud, to facilitate Global Positioning System (GPS)-enabled data collection, centralized storage, and real-time collaboration between field teams and office-based analysts. Field assessors collect the necessary data using Android devices, while QFieldCloud allows for synchronization with centralized databases. PostGIS stores geospatial data such as road condition attributes (e.g., potholes, rutting), hazard zones, and infrastructure features (e.g., culverts, ditches) together with environmental and socioeconomic factors. The system replaces traditional paper-based methods and enables segmentation of road stretches into 100-meter intervals for granular vulnerability analysis. Through participatory approaches, the architecture integrates local knowledge, such as previous disruptions caused by climate events, and utilizes a standardized 0–5 rating scale to assess road deficiencies. The results are analyzed and visualized in Microsoft Fabric (Power BI) utilizing a multidimensional road vulnerability index (RVI) model to highlight geographic disparities, support adaptation planning, and inform investment prioritization. Advanced analytics identify high-risk road segments, supporting targeted mitigation and policy actions. This integrated architecture provides a scalable, locally adaptable, and data-driven system for infrastructure resilience planning.

Figure 2 presents the innovative automated platform for collecting field data on road vulnerability. The platform captures geospatial data, including georeferenced road condition attributes (e.g., rutting, potholes, and washouts), mapped survey points, lines, and polygons representing affected segments, and contextual information such as land cover, flood zones, and elevation models. Key GeoPackage layers used in the assessment include road segments (classified by surface type, condition, and vulnerability status), drainage structures (e.g., culverts and ditches with condition data), observation points (geotagged notes and photographs of damage), and hazard zones (e.g., flood-prone, erosion, and landslide risk areas).

The data collection process comprises the following steps: (1) the project is created on a desktop with GeoPackage layers linked to a remote PostGIS database; (2) the project is uploaded to QfieldCloud using the QFieldSync plugin; (3) the QField app on Android mobile devices is synchronized with QfieldCloud; (4) multiple field users upload data changes to QfieldCloud; (5) all uploaded changes are automatically synchronized with the PostGIS database; (6) data from PostGIS is linked to Microsoft Power BI through an On-premises Data Gateway; (7) Power BI Dataflows perform extraction, transformation, and cleansing of the data; (8) semantic models organize the data by creating connections and relationships; and (9) reports are generated in a form of dashboards, maps, charts, etc. for analysis and decision-making.

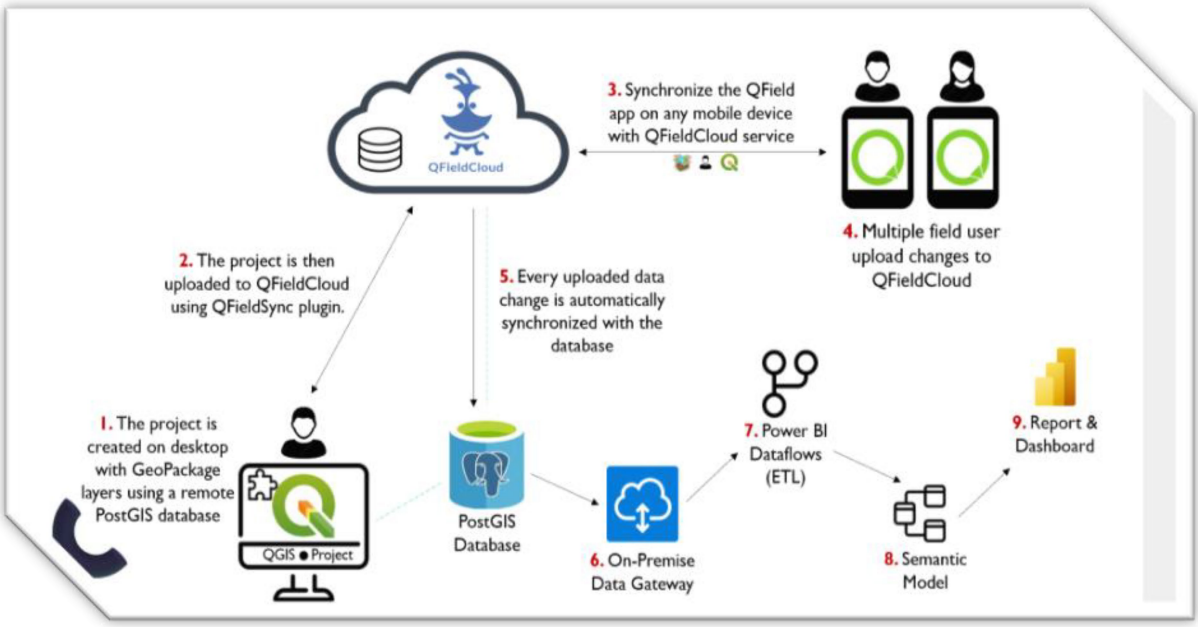


FIGURE 2
Data collection and analysis architecture developed for the road vulnerability assessment.

2.5 Indicators of the identified climate hazards

Indicators essential for characterizing climate variables and hazards within the proposed vulnerability assessment framework for unpaved secondary roads in Sierra Leone are critical for understanding infrastructure vulnerability. As noted by Zlateva and Hadjitodorov (2022), selecting appropriate indicators is a key step in assessing the sensitivity and exposure of infrastructure within specific geographic contexts. Indicators offer quantifiable metrics of parameters such as temperature extremes, precipitation levels, and wind speeds, enhancing our understanding of climate impacts (Zebisch et al., 2021). These metrics enable comparative analyses across hazards and regions, support trend identification, and assist in prioritizing interventions (Fleming et al., 2023). Furthermore, indicators aid stakeholders in interpreting complex climate data, thereby informing evidence-based decision-making and policy formulation (Sun et al., 2019). Table 1 summarizes the relevant climate variables, associated hazards, disaster-triggering indicators, and their impacts on infrastructure.

As illustrated in Table 1, extreme rainfall contributes to flooding, erosion, and infrastructure degradation, while extreme heat accelerates evaporation, weakens road materials, and exacerbates erosion. Wind and storms often result in structural failures and inundation. High humidity promotes material corrosion and slope instability, whereas sea-level rise leads to shoreline erosion and disrupts drainage systems. Additionally, drought conditions cause soil cracking and compromise the structural integrity of the road reserve. These impacts highlight the need for context-specific resilience strategies and prioritized maintenance planning in areas vulnerable to frequent and severe climate events.

2.6 Identification of potential climate variables and hazards that most affect the vulnerability of unpaved secondary roads

Climate variables and hazards that most significantly influence the vulnerability of unpaved secondary roads are essential components of the proposed vulnerability assessment framework. Recognizing these factors enables a more accurate evaluation of associated risks and vulnerabilities (Zlateva and Hadjitodorov, 2022). Studies have demonstrated that key climate variables and hazards adversely affecting unpaved roads include rainfall, temperature, wind speed, relative humidity, storms, flooding, drought, sea-level rise, wildfires, and landslides, among others (Mark Partington et al., 2018; Le Roux et al., 2019b; Le Roux et al., 2019a; Paige-Green and Verhaeghe, 2018; Verhaeghe et al., 2020; de Abreu et al., 2022). For example, Le Roux et al. (2019a,b) reported that elevated temperatures can negatively impact unpaved roads by increasing soil evaporation, reducing moisture content, intensifying dust generation, and heightening susceptibility to erosion and siltation during heavy rainfall. Moreover, the combination of higher temperatures and increased atmospheric CO_2 concentrations may promote rapid vegetation growth, potentially obstructing runoff drainage from the road reserve (Le Roux et al., 2019b; Le Roux et al., 2019a).

Ngezahayo et al. (2021) reported that unpaved roads are highly influenced by climate factors such as temperature and rainfall. Under dry conditions, soil surfaces are particularly susceptible to erosion due to elevated temperatures and traffic-induced shear stresses, while dislodged materials are prone to transport by rainwater splashing or surface runoff. Similarly, Lera and Kuleno (2020) found that intense rainfall, combined with the inherent weakness and lack of cohesion in pavement materials, significantly contributes to the degradation of unpaved roads. Among climate variables, rainfall, particularly its intensity, represents a primary influencing factor. Changes in seasonal precipitation patterns and river flow, along with rising sea levels and elevated temperatures, pose considerable risks to unpaved roads (de Abreu et al., 2022). These factors contribute to increased surface runoff, flooding, landslides, slope failures, and structural road damage during periods of intense rainfall. Additionally, de Abreu et al. (2022) asserted that rising sea levels exacerbate flooding risks and accelerate the failure of road pavements and embankments, while saturated conditions reduce the lifespan of pavement layers. Storm surges, coupled with strong winds and frequent cyclones, cause coastal infrastructure inundation, erosion of road bases and bridge supports, and disruptions due to debris accumulation on roadways (de Abreu et al., 2022).

Solomon et al. (2022) revealed that Sierra Leone lacks sufficient climatic data necessary for informed decision-making. However, using a global circulation model, they applied a global circulation model and identified several key climate variables—namely rainfall, temperature, wind speed, relative humidity, and solar radiation—as major threats. These variables vary significantly and are projected to continue varying in the coming decades. Similarly, the World Bank Disaster Risk Management Diagnostic Note highlighted multiple climate-related hazards affecting Sierra Leone, including high temperatures and humidity, which elevate heat index values that impact various economic sectors; extreme rainfall events, which trigger flash floods, riverine flooding, and landslides across the country; and rising sea levels, which intensify coastal erosion and compound the risks associated with climate change. Additionally, the report emphasized the country's exposure to frequent floods, storms, and fires, underscoring its vulnerability to natural disasters (World Bank, 2020). From this context, the key climate factors that influence the vulnerability of unpaved road infrastructure, including rainfall, temperature, wind speed, relative humidity, storms, flooding, drought, sea-level rise, wildfires, and landslides, fluctuate across Sierra Leone. Moreover, studies have projected their continued intensification in the coming decades (World Bank, 2020).

2.7 Vulnerability assessment framework for unpaved secondary roads

The final output is a locally adapted vulnerability assessment framework that integrates technical analysis with stakeholder input and combines global best practices with context-specific realities. Central to this framework is the data collection and analysis platform illustrated in Figure 2, which enables efficient, GPS-enabled field data gathering, centralized geospatial processing, and interactive visualization. The framework supports data-driven decision-making for prioritizing unpaved road infrastructure in national climate adaptation strategies. Figure 3 presents the proposed integrated system for assessing the climate risk and vulnerability of unpaved secondary roads in Sierra Leone. The proposed vulnerability assessment framework for unpaved secondary roads in Sierra Leone adopts a structured, five-phase

TABLE 1 Climate variables, associated indicators, and impact factors.

Climate variable	Climate events/ Hazards	Climate variables and hazard indicators	Factors impacting unpaved road infrastructure and its components
Extreme Rainfall/Heavy Precipitation	Extreme high rainfall in 24-h/Sustained rainfall/ Antecedent rain followed by a significant rain event. High-intensity rainfall, Spatial extent, intensity, frequency Increased rainfall	1-day rainfall > 65 mm/3-day rainfall > 115 mm/14-day, antecedent rainfall > 80 mm, followed by days per year with rainfall above 20 mm in 24 h/20-year return period annual maximum 1-day and 3-day precipitation, average annual rainfall (Mark Partington et al., 2018) Flooding (Le Roux et al., 2019b; Le Roux et al., 2019a) Soil and construction material strengths (Le Roux et al., 2019b; Le Roux et al., 2019a)	Mark Partington et al. (2018): • High runoff, culverts and bridges damaged or destroyed, road surface damage or deterioration, and safety. • High runoff and saturated soil impacts to cut/fill slopes, landslides, culverts, ditches, catch basins; • Flooding leading to road components (pavement, embankments, culverts, etc.), washouts and mudslides that damaged roads, erosion, scouring, etc. • Erosion of cut fill, embankments, and slopes • Isolation of communities, road and infrastructure damage; the greatest risk to infrastructure, economic losses (Le Roux et al., 2019b; Le Roux et al., 2019a) • Reduced strengths, rapid erosion, siltation, increased vegetation growth, and drainage system strain (Le Roux et al., 2019b; Le Roux et al., 2019a)
Extreme heat/ Temperature	Hot days and heatwaves (daily temperature variation), including maximum and minimum	Days with daily temperature variation > 35°C (Mark Partington et al., 2018)	• Thermal expansion/contraction of bridge joints and paved sections; • Increased evaporation from the soil causes a reduction in moisture content (unpaved roads), leading to more dust emissions • Increased susceptibility to erosion and siltation in the event of heavy rains after a long dry spell
Wind and Storms	Storm surges	Above 100 mph or (53.3 m s^{-1} to 11.6 m s^{-1}); and flooding above one foot (Středová et al., 2021)	• Greater probability of road infrastructure failures • Rainfall and winds associated with storms /cyclones will create flooding, inundate embankments, and affect roads (Haq et al., 2022)
Increased Relative Humidity (increased water vapor in the air)	Increased moisture in the atmosphere/heat stress, and heat-related illness exacerbate the effects of heat	RH levels above 80–85% trigger corrosion coupled with other factors, including temperature, exposure to pollutants, precipitation, etc., RH levels above 70–80% over an extended period can contribute to saturated soil conditions, depending on the region, and RH levels between 70 and 80% accelerate the degradation of road signs, etc.	• Corrosion of metal components in bridges, guardrails, etc. • Reduced visibility for drivers due to fog formation, thus increasing the risk of accidents. • Excessive moisture in the soil can destabilize slopes and embankments, increasing the risk of landslides and road failures in hilly/mountainous terrain. • Accelerate the degradation of road signage, guardrails, and other roadside infrastructure through rusting/corrosion, etc., requiring more frequent maintenance/ replacement.
Sea level rise		Based on regional and local scales (5–15 cm)	• Inundation of low-lying areas; erodes Cut fill, embankments, and slope; increases flooding from storm surges and rainstorms and enables salt water to advance upstream; drainage systems become less effective; loss of roads parallel to shorelines (Haq et al., 2022)
Drought Conditions	Days without rain from very high to severe; Reduced rainfall/drier periods	Soil desiccation (Le Roux et al., 2019b; Le Roux et al., 2019a)	• Wildfire hazards, increased hydrophobic soils, dusty conditions; Soil cracking, compromised road reserve (Le Roux et al., 2019b; Le Roux et al., 2019a)

approach adapted from global best practices, offering a practical and context-specific process for implementation. It integrates cost-effective tools and stakeholder engagement to enhance the relevance and usability of results for decision-makers. Figure 3 illustrates the methodological flowchart of the vulnerability assessment framework.

In the first phase, the target infrastructure (unpaved secondary roads) is defined, and key data are collected on historical weather-related events, climate information, road conditions, usage, community perceptions, and socio-environmental factors, such as population distribution and access to alternative routes. In addition, understanding the geographic context is crucial at this stage. In the second phase, the framework employs tools such as QGIS and QField for GPS-enabled mobile data collection, supported by cloud-based storage systems. A local community perception survey on climate change and its implications for unpaved roads is also conducted. This phase emphasizes stakeholder involvement to ensure community-relevant data and strengthen local ownership of the assessment process. In the third phase, climate risk is analyzed through the identification of trends, variability, forecasting and extreme events over the past 30 years. International Business Machines (IBM) Statistical Package for the Social Sciences is used to analyze local community perceptions of climate change and

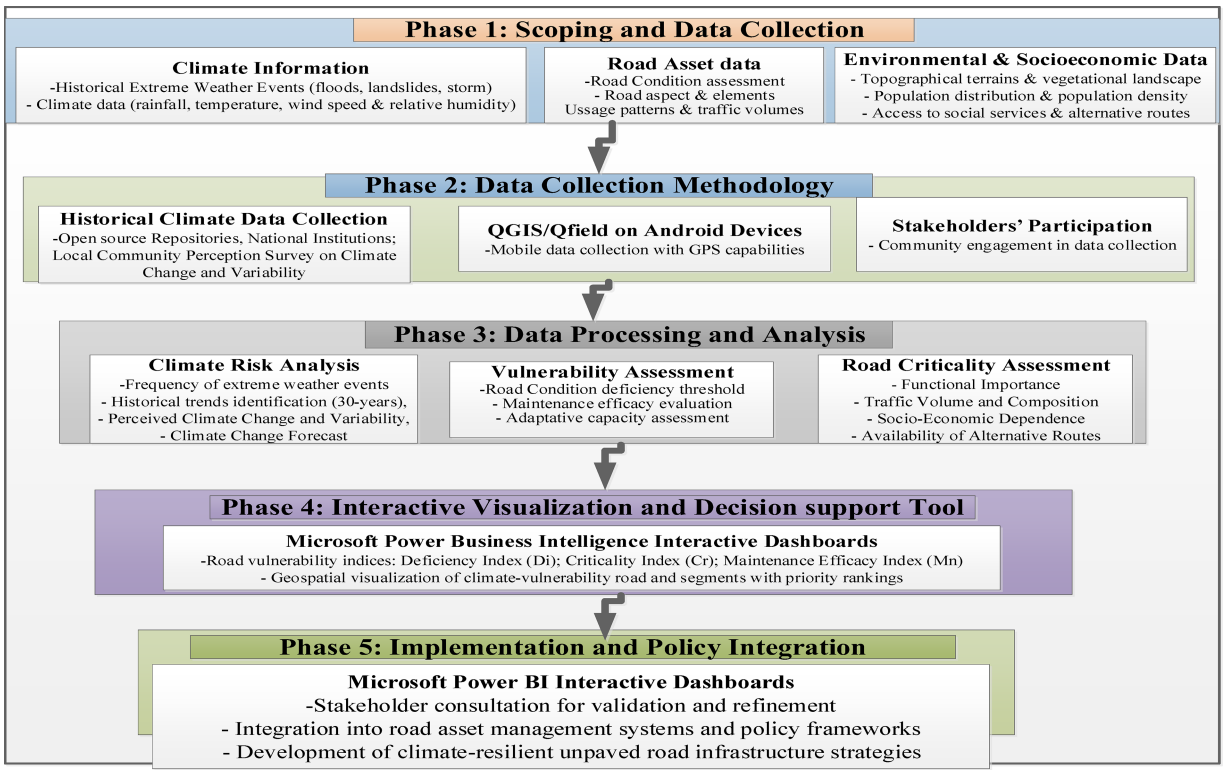


FIGURE 3
Vulnerability assessment framework.

variability. Includes the use of Microsoft Power Business Intelligence (BI) for road condition deficiency analysis, maintenance efficacy evaluation, and assessments of adaptive capacity and road criticality, based on factors such as functional importance, usage levels, and availability of alternative routes. In the fourth phase, Microsoft Power BI is used to present the findings through dynamic dashboards. These dashboards present composite indices, including the deficiency index (D_i), maintenance index (M_n), and criticality index (C_r), and generate geospatial maps to identify and rank vulnerable road segments for prioritized action. In the fifth phase, the assessment findings are translated into practice by informing infrastructure adaptation strategies, asset management planning, and policymaking. This phase includes stakeholder consultations for validation and promotes iterative monitoring and refinement of interventions to ensure long-term resilience. Together, these phases form a holistic framework that quantifies vulnerability and supports targeted, evidence-based adaptation and policy decisions for improving the resilience of unpaved secondary roads in Sierra Leone.

3 Methodology overview

This study employed a mixed-methods approach to develop a framework for assessing the vulnerability of unpaved secondary roads to climate change in Sierra Leone. The methodology integrates a systematic literature review, quantitative and spatial analysis, case study evaluation, and composite index development to capture the exposure, sensitivity, and adaptive capacity dimensions (Gobo, 2023). Figure 4 presents the methodological flowchart guiding this study.

3.1 Literature review

The literature review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses protocol and sourced peer-reviewed articles published between 2014 and 2025 from databases such as Scopus and Web of Science, using keywords such as 'road vulnerability', 'climate adaptation', and 'unpaved roads'. Inclusion criteria encompassed studies with clear methodologies and relevance to developing countries, while exclusion criteria comprised non-English and non-empirical studies. This review provided information on the adaptation of international assessment frameworks, such as that of Le Roux et al. (2019a,b), to local contexts. Quantitative data, including climate variables (e.g., rainfall, flood frequency) and infrastructure condition data, were analyzed to evaluate exposure and sensitivity, as defined by the Federal Highway Administrations (FHWA) (2017), while Geographic Information System (GIS)-based spatial analysis identified roads located in climate-vulnerable zones (Nunfam, 2021). Statistical methods, such as correlation and regression analysis, were applied to determine the relationships between climate factors and road deterioration. Complementing these, case studies drawn from selected corridors provided local insights through maintenance records, field observations, and community interviews, allowing the triangulation of findings. Similarly, the exposure analysis of identified climate hazards for the infrastructure under review utilized research-based forecasts and simulation results from climate models that accounted for potential future climate change. Relevant models and projections were sourced from

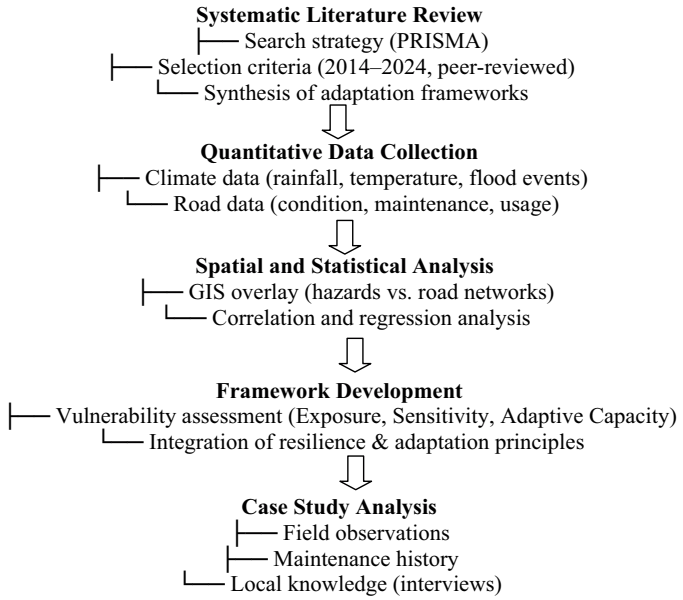


FIGURE 4
Methodological flowchart guiding this study.

authoritative and widely recognized datasets and platforms, as recommended by Zlateva and Hadjitodorov (2022):

1. Copernicus Climate Change Service, which provides authoritative information about the past, present, and future climate change service Climate Data Store (CDS) (2022), which offers historical, current, and projected climate information through the climate data store.
2. Coordinated Regional Climate Downscaling Experiment [Coordinated Regional Climate Downscaling Experiment (Cordex), 2022] providing global and regional climate simulations and statistical downscaling outputs.
3. European Environment Agency (2022), via the European Climate Adaptation Platform (Climate-ADAPT)
4. Adam (2022) for statistical time series ARIMA modeling applied to near-term point forecasts.

These inputs informed the development of a localized framework grounded in the principles of exposure, sensitivity, and adaptive capacity (Zlateva and Hadjitodorov, 2022) and integrating the concepts of resilience and adaptation to support practical decision-making by road agencies.

The Federal Highway Administrations (FHWA) (2017) defines vulnerability in transportation as the degree to which a system is exposed to climate effects, as well as its sensitivity and capacity to adapt. Sensitivity describes the degree to which an asset or system is affected by climatic stressors, with highly sensitive assets experiencing substantial impacts from even minor climatic variations, whereas lesssensitive assets exhibit greater tolerance. Exposure indicates whether an asset is located in an area subject to climate variability or extreme weather events, serving as a foundational element of vulnerability. Resilience is defined as the ability to anticipate, plan for, adapt to, and recover quickly from disruptions, while adaptation involves adjusting or maintaining transportation assets to respond to environmental changes, thereby maximizing benefits and minimizing adverse impacts. The development of the proposed framework commenced with a review of existing techniques, which assessed their effectiveness across different scales of road vulnerability assessment using methodologies established by international aid organizations.

3.1.1 Climate risk and vulnerability assessment approaches for critical infrastructure

Globally, several approaches have been developed to assess the impacts of climate change on critical infrastructure. This study classifies these approaches into five broad categories: scenario-based, index-based, process-based, spatial, and integrated assessments. Scenario-based assessments project future climate conditions under different emission pathways or models to explore potential impacts on infrastructure and inform adaptation strategies (Gaarder et al., 2023). Index-based assessments quantify vulnerability using indicators that span physical, social, economic, and environmental factors (Le Roux et al., 2019b; Le Roux et al., 2019a). These indicators are aggregated into indices to facilitate comparison across regions. Process-based assessments investigate interactions between climate stressors and infrastructure systems by examining exposure, sensitivity, and adaptive capacity (Le Roux et al., 2019b; Le Roux et al., 2019a). Spatial assessments leverage GIS and spatial modeling to map the geographical distribution of climate risks and vulnerabilities, incorporating land use and infrastructure data. Integrated assessments combine elements of these approaches to capture the complexity of climate-infrastructure interactions (Khemesh, 2025). Using these methods, stakeholders can gain a nuanced understanding of climate-related risks and design effective adaptation strategies, particularly for critical systems such as transport infrastructure. Process-based vulnerability assessments of climate change involve a systematic approach to identifying, analyzing, and prioritizing the potential impacts of climate change on a specific system or region and

considering both the exposure to climate hazards and the system's sensitivity and adaptive capacity. For instance, the UNCTAD (2017) framework for assessing climate change impacts on coastal transportation infrastructure in the Caribbean adopts a process-based vulnerability assessment approach, focusing on exposure, sensitivity, and adaptive capacity to enhance the resilience of Small Island Developing States.

Vulnerability assessments can provide an enhanced understanding of both community and environmental needs related to capacity-building and identify appropriate adaptation and mitigation measures (de Sherbinin et al., 2019). Despite widespread development, many vulnerability assessment frameworks, including those presented in Table 2, face similar limitations. These include reliance on costly proprietary software, high computing infrastructure, high data and technical requirements, narrow geographic applicability, and limited flexibility for local adaptation and stakeholder engagement amid diverse climate, infrastructure, and socio-economic contexts. A core challenge is that vulnerability is not directly measurable; rather, it is a multidimensional concept shaped by interacting physical, socioeconomic, and cultural factors, which vary over time and space. As a result, confusion often arises between index-based and indicator-based approaches, and many frameworks struggle to reflect the lived realities of vulnerable communities (de Sherbinin et al., 2019).

Against this backdrop, this study reviewed key climate risk and vulnerability assessment frameworks to identify the most appropriate model for application in Sierra Leone. Prominent frameworks include the World Bank's Climate and Disaster Risk Screening Tools (2022); the FHWA Vulnerability Assessment Framework (2017), the risk management for roads in changing climate (RIMAROCC); Framework based on Climate-ADAPT The European Climate Adaptation Platform Climate-ADAPT, (2023), the Public Infrastructure Engineering Vulnerability Committee (PIEVC) Protocol (2018), the Asian Development Bank (ADB) Guidelines for Climate-Proofing Investment in the Transport Sector [Asian Development Bank (ADB), 2011], and the Risk Management and Resilience Optimization for Vulnerable Access Roads framework developed under ReCAP (Le Roux et al., 2019b; Le Roux et al., 2019a). These frameworks provide structured approaches for assessing climate risk but share common limitations, including reliance on standardized formats, use of costly proprietary software (e.g., ArcGIS, MATLAB, HEC-RAS), high data and technical requirements, and limited adaptability to local socio-economic and geographic contexts. Frameworks such as PIEVC and ADB Guidelines require significant modification to suit Sierra Leone's climate, infrastructure conditions, and institutional capacities. Similarly, the ReCAP framework focuses on vulnerable access roads and encourages local engagement, but its broader applicability is limited by scalability and capacity constraints.

Given the limitations of existing frameworks, conducting effective vulnerability assessments in Sierra Leone, particularly for unpaved roads, requires flexible, context-specific approaches that combine technical rigor with strong local engagement.

Unlike conventional models that rely on large datasets, expensive proprietary software, or high-end computing infrastructure requiring highly specialized expertise, this framework adopts a flexible five-step process where exposure and sensitivity determine potential impacts, moderated by adaptive capacity. By ranking sector vulnerabilities as low, medium, or high, the framework enables policymakers, engineers, and local stakeholders to identify priority areas for intervention more effectively [Climate System Analysis Group (CSAG), 2020]. While informed by international best practices (Zlateva and Hadjitodorov, 2022; Zebisch et al., 2021), the framework is structured to accommodate local infrastructural realities, ensuring a more actionable and context-specific vulnerability assessment. The implementation strategy consists of five methodological steps, detailed in the following sections.

As presented in Table 2, climate risk and vulnerability assessment frameworks vary in their suitability depending on regional context, data availability, and stakeholder engagement. Selecting an appropriate framework requires balancing technical feasibility with local adaptability. The following sections present the proposed framework developed in this research, which integrates tools and methodologies designed to address the implementation challenges identified in prominent international frameworks for assessing climate risk and vulnerability in road infrastructure, as outlined in Table 2.

3.1.2 Vulnerability levels of unpaved secondary roads to identified climate hazards

The vulnerability levels of the infrastructure under review were determined by combining analyses of sensitivity and exposure to identified climate hazards and variables within the specific geographic region, by the IPCC approach [Climate System Analysis Group (CSAG), 2020]:

$$\text{Exposure} + \text{Sensitivity} = \text{Potential Impact} + \text{Adaptive Capacity} = \text{Vulnerability}$$

In the proposed vulnerability assessment framework for unpaved secondary roads, the vulnerability levels were determined by following the steps outlined in the ReCAP guidelines:

1. The geometric mean was computed based on the severity and extent of distress (physical damages or defects observed on the road surface, such as cracks, potholes, and rutting) for each unpaved secondary road infrastructure element within each segment and across the entire road stretch. The geometric mean combines multiple vulnerability factors of road infrastructure, such as exposure, sensitivity, and adaptive capacity, into a single composite score by multiplying their values and taking the nth root, where n is the number of factors. This approach balances each indicator's influence by minimizing extremes and ensuring that a low score in any dimension significantly lowers the overall vulnerability, reflecting the need to consider all factors collectively.
2. The maximum value among the computed geometric means of the elements under each infrastructure aspect was selected for each segment and the entire road stretch.
3. The median was calculated from the selected maximum geometric means for each segment and the entire road stretch.
4. The average of the medians across all segments was calculated as the overall vulnerability level of the unpaved secondary road infrastructure.
5. This procedure was repeated for three dimensions: infrastructure condition, maintenance regime, and criticality, represented by D_i, M_n, and C_r, respectively.
6. These indicators were treated as composite indicators contributing to the RVI.

TABLE 2 Comparative assessment of notable vulnerability assessment frameworks.

Framework	Geographical adaptability	Flexibility	Data requirements	Stakeholder engagement	Costly software and high computing infrastructure	Implementation challenges	Research approach classification
World Bank Climate & Disaster Risk Screening Tool	A global but standardized approach may not fully capture	Moderate; allows project-level adjustments	High; requires technical expertise & climate projections	Limited, primarily expert-driven	Moderate to High	Data constraints, limited local customization, and macro-level focus	Scenario-Based Assessment
FHWA Climate Change & Extreme Weather Vulnerability Assessment	Developed for the U. S., applicability may require adjustments for other regions.	Highly structured but adaptable methodology	High; requires historical climate data and risk modeling	Moderate; some stakeholder inclusion	Moderate to High	Data constraints, complex modeling, need for local calibration	Process-Based Assessment
RIMAROCC Framework	Developed for European roads; requires adaptation for other climates	Moderate; structured but adaptable process	High; extensive data on road infrastructure & climate hazards	Limited, mainly expert-driven	Moderate to High	Requires strong institutional capacity, technical expertise, and local data availability	Process-Based Assessment
PIEVC Framework	Designed for Canada but applicable globally with modifications (Mark Partington et al., 2018)	High; adaptable to various infrastructure types (Mark Partington et al., 2018)	High; engineering and climate data-intensive (Mark Partington et al., 2018)	Strong; promotes stakeholder engagement (Mark Partington et al., 2018)	Moderate to High	Introduces complexity, the need for technical capacity, requires customization for different contexts (Mark Partington et al., 2018).	Process-Based Assessment
ADB Guidelines for Climate-Proofing Transport	Asia-focused; adaptation needed for other regions	High; provides general guidelines applicable across regions	Moderate; requires climate risk assessment & infrastructure data	Strong; emphasizes capacity building and policy integration	Low to Moderate	Assumptions about governance and financing may not align with other regions	Integrated Assessment Approach (scenario analysis, risk assessment, and policy/institutional)
European Climate Adaptation Platform (Climate-Adapt)	EU-focused; applicability outside Europe requires adjustments	Moderate; database of best practices but less adaptable to non-EU settings	High; climate data, case studies, and adaptation strategies	Moderate; knowledge-sharing focus, but limited direct local engagement	Low to Moderate	European-specific conditions may not align with other regions' needs	Integrated Assessment Approach (knowledge-sharing and policy-support platform)
ReCAP Framework (Risk Management & Resilience Optimization for Vulnerable Access Roads)	Africa & low-income regions focused; suitable for community-based adaptation (Le Roux et al., 2019b; Le Roux et al., 2019a)	High; emphasizes local adaptation and low-cost resilience measures (Le Roux et al., 2019b; Le Roux et al., 2019a)	Low to moderate; focuses on empirical data and local knowledge (Le Roux et al., 2019b; Le Roux et al., 2019a)	Strong; highly participatory, involving local communities (Le Roux et al., 2019b; Le Roux et al., 2019a)	Low	Limited scalability, resource constraints, technical capacity challenges, cumbersome process (Le Roux et al., 2019b; Le Roux et al., 2019a)	Integrated Assessment Approach (process-based, index-based, and participatory approaches)

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7. The combination of D_i, M_n, and C_r produced a quantifiable RVI, with values ranging from 1 to 5.

The four levels of the RVI are defined as follows:

1. Very high vulnerability ($4 < RVI \leq 5$): the unpaved road infrastructure at a specific location was considered very highly vulnerable to the identified climate hazards and relevant climate variables
2. High vulnerability ($3 < RVI \leq 4$): the unpaved road infrastructure at a specific location was considered highly vulnerable to the identified climate hazards and relevant climate variables
3. Medium vulnerability ($2 < RVI \leq 3$): the unpaved road infrastructure at a specific location was considered moderately vulnerable to the identified climate hazards and relevant climate variables
4. Low vulnerability ($1 < RVI \leq 2$): the unpaved road infrastructure at a specific location was considered to have low vulnerability to the identified climate hazards and relevant climate variables.

Furthermore, the vulnerability levels were determined using the Microsoft Power BI platform (Microsoft Fabric). This platform generates visualization tools—including maps, charts, graphs, matrices, and query reports, that illustrate the key factors influencing the RVI. Key factors contributing to the system's challenges encompass maintenance lapses and criticality stemming from a lack of alternative routes. The vulnerability maps produced through Microsoft Fabric provided critical insights into areas expected to experience significant societal impacts, thereby guiding stakeholders in formulating essential adaptation strategies (de Sherbinin et al., 2019). These interactive tools played a pivotal role in informing decisions related to the allocation of billions of dollars in adaptation funding, particularly within frameworks such as the Green Climate Fund (de Sherbinin et al., 2019). The RVI calculations conducted within Microsoft Fabric incorporated geomorphological terrain, vegetational landscapes, topographical features, river basin contributions, soil composition, and population distribution and density. This comprehensive approach to vulnerability assessment aligns with the findings of previous studies (Le Roux et al., 2019b; Le Roux et al., 2019a; Paige-Green and Verhaeghe, 2018; Verhaeghe et al., 2020; Madushani et al., 2024) and is expressed in Equation 1 as follows:

$$RVI = D_i^a \times M_N^B \times M_r^c \quad (1)$$

3.1.3 Sensitivity of unpaved secondary roads to the identified hazards

The proposed vulnerability assessment framework recommends conducting sensitivity analyses on infrastructure components to evaluate their susceptibility, regardless of their proximity to identified hazards. This analysis considers the overall functionality of the infrastructure, along with its direct and indirect interactions with other systems under climate hazard conditions. It incorporates quantitative data, qualitative assessments, and expert judgment as key inputs. For unpaved secondary roads, the framework identifies seven key component areas, each with specific elements: (1) Erodibility factors, such as drainage, road surface, side drains, and embankment slopes; (2) Drainage over streams, which involves structures, approach fills, and erosion protection, and subgrade issues, such as material type and moisture content; (3) Slope stability for both cuts and fills; (4) Drainage within the road reserve, including the road shape and shoulder conditions; (5) Construction quality and erosion protection measures; (6) Maintenance quantity and quality; and (7) Criticality factors, such as access to public facilities, alternative road availability, and typical vehicle types used.

The sensitivity assessment of unpaved secondary road infrastructure to identified climate variables and hazards was conducted by assigning ratings to the current condition of the infrastructure, the maintenance regime, and its criticality. Experts recommend using a school grade-type scheme, typically a scale from 1 to 5, to facilitate effective communication (Zebisch et al., 2021). The roads were pre-segmented into 100-meter intervals, within which each road component was evaluated based on two criteria: the degree of distress (severity) and the extent of distress (spread), which were both rated on a scale from 0 to 5 (Le Roux et al., 2019b; Le Roux et al., 2019a). This evaluation was carried out for all elements of unpaved secondary roads across each identified aspect, including maintenance effectiveness and criticality.

The framework categorizes sensitivity into four levels:

1. Not sensitive (0): No observable impact from climate hazards.
2. Low sensitivity (1–2): Acceptable condition, with minimal expected impact.
3. Medium to high sensitivity (2–3): Potential for moderate to significant impact.
4. Very high sensitivity (3–5): Severe impact likely under climate hazards.

3.1.4 Exposure of unpaved secondary road infrastructure to the identified climate hazards

The proposed vulnerability assessment framework incorporated location-specific climate conditions by integrating historical and projected climate data from international and national sources using GIS. The exposure analysis considered key variables such as precipitation, temperature, wind speed, and relative humidity, based on historical records (1991–2021) and a 30-year climatological baseline from NASA POWER (Stackhouse and Kusterer, 2000; Tayyeh and Mohammed, 2023). Additional datasets included EM-DAT, IPCC TG-Data, IMF Climate Data, and the World Bank Climate Change Portal [IMF-Climate data, 2022; Intergovernmental Panel on Climate Change (IPCC), 2022; World Bank, 2022; Emergency Events Database (EM-DAT), 2023]. A near-term forecast was generated using an ARIMA statistical time-series model. Detailed data sources are provided in the Supplementary material.

4 Case study analysis

4.1 Applicability of the proposed framework by road agencies in managing road infrastructure

To evaluate the effectiveness of the proposed vulnerability assessment framework in enhancing the resilience of unpaved secondary roads to current and future climate hazards and variability,

the framework was applied to four unpaved secondary roads across four distinct geographic regions in Sierra Leone. Each road was analyzed within the framework to identify region-specific climate variables influencing vulnerability and to assess multiple contributing factors. These included the road's current condition and components, topographical features, vegetational landscape, adjacent river basins, geological and soil characteristics, road geometry, traffic volume, accessibility to public facilities, the availability and condition of alternative routes, population distribution and density, presence of watercourses, and maintenance regime. These factors were assessed to determine the sensitivity (S_i) to current and future climate exposures (E_{ci}, E_{fi}), the adaptive capacity (A_{ci}) of the roads, and their criticality (C_{ri}) to the communities they serve. The adaptive capacity and sensitivity contributed to road condition deficiencies and maintenance efficacy, which together with road criticality form the RVI.

The selected roads were segmented into 100-meter intervals using QGIS plugins. Field data were synchronized through QFieldCloud and transferred to a PostGIS database for real-time analysis. A participatory approach enriched the dataset with local knowledge, including historical data on weather-related events such as floods and landslides, as well as infrastructure conditions. Trained field assessors evaluated road deficiencies using a standardized 0–5 rating scale aligned with international vulnerability assessment frameworks. Collected data on climate threats, geospatial features, and socioeconomic variables were analyzed in Microsoft Fabric using the Multi-dimensional RVI. The Multi-dimensional RVI is a composite metric that quantifies the susceptibility of road segments to damage or disruption by integrating multiple factors, such as structural condition, exposure to climate hazards, environmental sensitivity, and accessibility importance, into a single, spatially-referenced score (Le Roux et al., 2019b; Le Roux et al., 2019a). Advanced analytics and interactive dashboards were employed to visualize climate risks. This integrated system facilitated data-driven decision-making, allowing for the precise identification of both critical road segments and broader areas requiring adaptation and mitigation interventions. Based on a combination of geospatial technology, automated data processing, and community engagement, this study established a replicable and scalable framework for climate-resilient road infrastructure planning, representing a significant advancement in road vulnerability assessment methodologies.

Inputs obtained through a community participatory approach, including location and frequency of road cut-offs, accident incidence due to adverse weather, remedial coping practices undertaken by communities prior to the arrival of road managers, and the frequency and quality of road maintenance, facilitated the refinement of information fed into the Microsoft Fabric platform. Figure 5 illustrates the outputs from the framework for the case study of npaved secondary roads combined (North, South, East, and West).

Figure 5 presents a section of a vulnerability assessment matrix for four unpaved secondary roads, each representing one of Sierra Leone's four regions. The data, collected using simple, open-source, and low-cost technologies (as detailed in Appendix 3), assesses physical and environmental stressors across road segments defined by chainage. The RVI of 4.06 reflects a high level of overall vulnerability across the assessed unpaved roads. The most critical stressors include inadequate drainage reserves, such as poorly designed side slopes, side drains, and embankments, alongside the complete absence of alternative routes and significant issues with moisture-sensitive subgrades and unstable fill/cut slopes.

A general maintenance score of 4.0 further underscores the inconsistency in intervention quality and frequency. Erosion risks from exposed subgrades and unlined drains, combined with insufficient protection around drainage streams, leave the roads particularly prone to washouts during heavy rainfall. Regional terrain and climate variations suggest slope instability is most severe in the East and South, drainage deficiencies dominate the rapidly urbanizing West, and erosion-related vulnerabilities are more pronounced in the wind-exposed North. Additionally, a general criticality score of 3.5 indicates that these roads are highly important, providing access to economic hubs and public facilities for the communities they serve, yet remain highly vulnerable. These insights call for climate-informed, district-level planning that incorporates both instrumental data and local knowledge.

This result can be displayed as interactive maps using the visualization tool of Microsoft Power BI, which forms part of the framework. This mapping capability is a key strength of the platform, enabling spatial representation of road vulnerability and criticality, an important feature often missing in generic assessment frameworks. The integration of visual mapping into the framework enhances decision-making by allowing stakeholders to easily identify high-risk segments and prioritize interventions based on location-specific data.

Figure 6 illustrates the vulnerability assessment indices for the case study of unpaved road 1: Mathoir–Masemera road in the Northern province in the form of a map.

Figure 7 illustrates the vulnerability assessment results for unpaved secondary roads in the Northern region. It indicates a high level of vulnerability to climate change impact, with an overall RVI of 3.62 on a 1–5 scale. This is driven by a severe road condition deficiency ($D_i = 3.9$), suggesting significant deterioration. The relatively high maintenance efficacy score ($M_n = 3.0$) reflects insufficient maintenance responses to existing challenges. Additionally, a criticality score of 3.1 highlights the moderate socioeconomic importance of these roads. These findings underscore the urgent need for targeted interventions to improve resilience and functionality.

Figure 8 illustrates the vulnerability assessment indices for the case study of road 2: Malema Junction–Sulima Spur road in the Southern province in the form of a map.

Figure 8 illustrates that unpaved secondary roads in the Southern region are highly vulnerable, with an overall RVI of 3.73. The high road condition deficiency ($D_i = 3.9$) indicates severe deterioration. The relatively high maintenance score ($M_n = 3.5$) suggests significant maintenance needs, either due to infrequent interventions or substandard work that fails to ensure resilience to climate change and variability. A criticality score of 3.1 reflects moderate socioeconomic importance. These results call for more effective and climate-responsive maintenance strategies.

Figure 9 illustrates the vulnerability assessment indices for the case study of road 3: Kenema—Zimmi road in the Eastern province in the form of a map.

Figure 9 shows that unpaved secondary roads in the Eastern region are highly vulnerable, with an overall RVI of 3.81. The road condition deficiency is severe ($D_i = 4.0$), indicating extensive deterioration. The relatively high maintenance score ($M_n = 3.7$) reflects significant maintenance needs either due to infrequent interventions or poor-quality works that fail to ensure resilience against climate change and variability. The criticality score of 3.1 indicates moderate socioeconomic relevance. These findings underscore the need for improved, climate-resilient maintenance strategies.

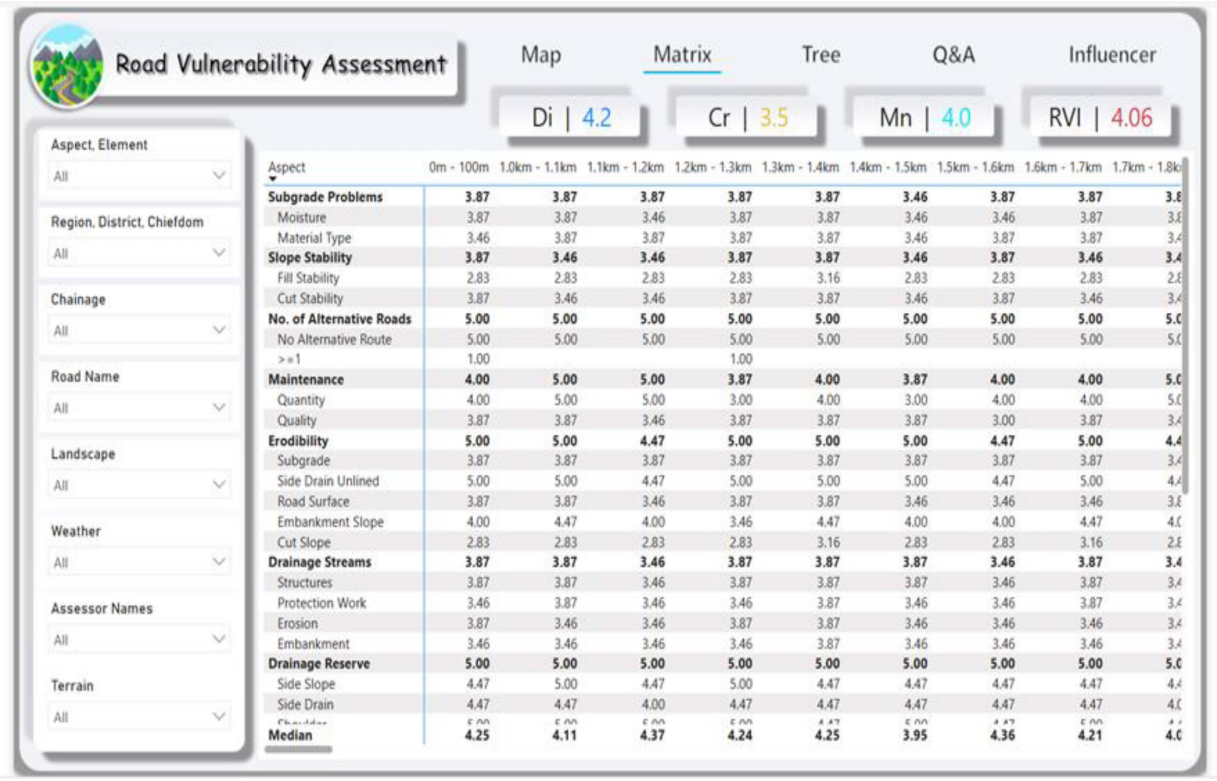


FIGURE 5
Results of the vulnerability assessment analysis for the four unpaved secondary roads.

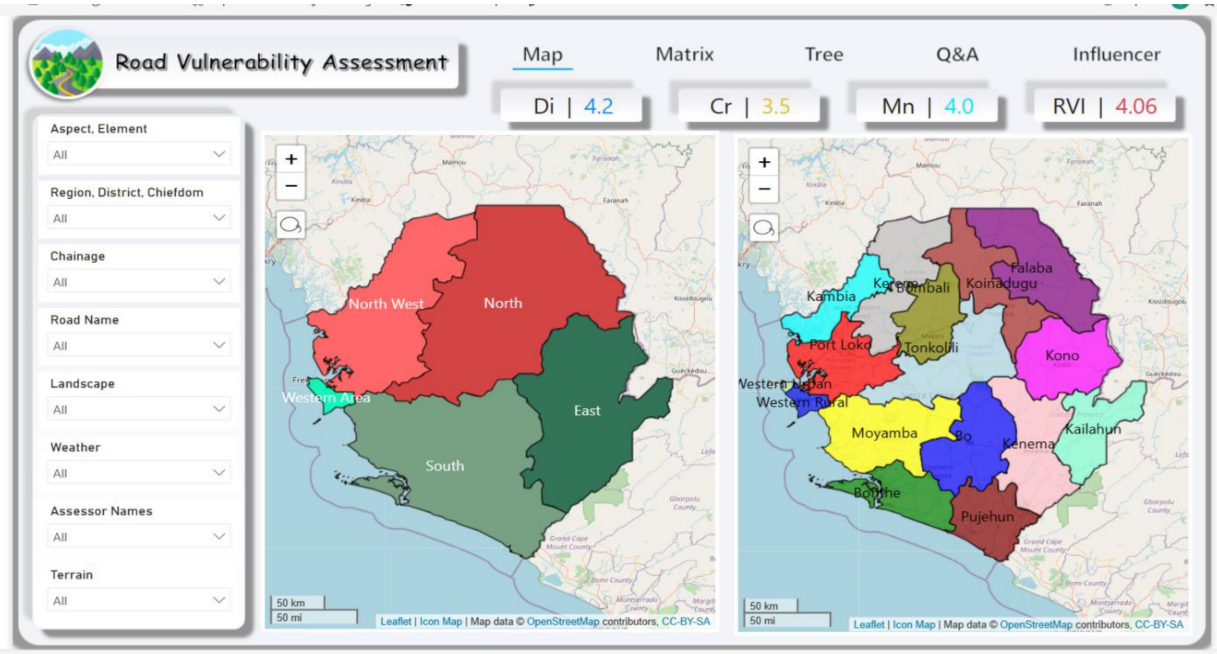


FIGURE 6
Nationwide vulnerability assessment maps for unpaved road.

Figure 10 illustrates the vulnerability assessment indices for the case study of road 4: Malembe road in the Western region in a map form.

Figure 10 shows that unpaved secondary roads in the Western Region are highly vulnerable, with an overall RVI of 3.81 on a 1–5 scale. The road condition deficiency is severe ($D_i = 4.0$), indicating significant

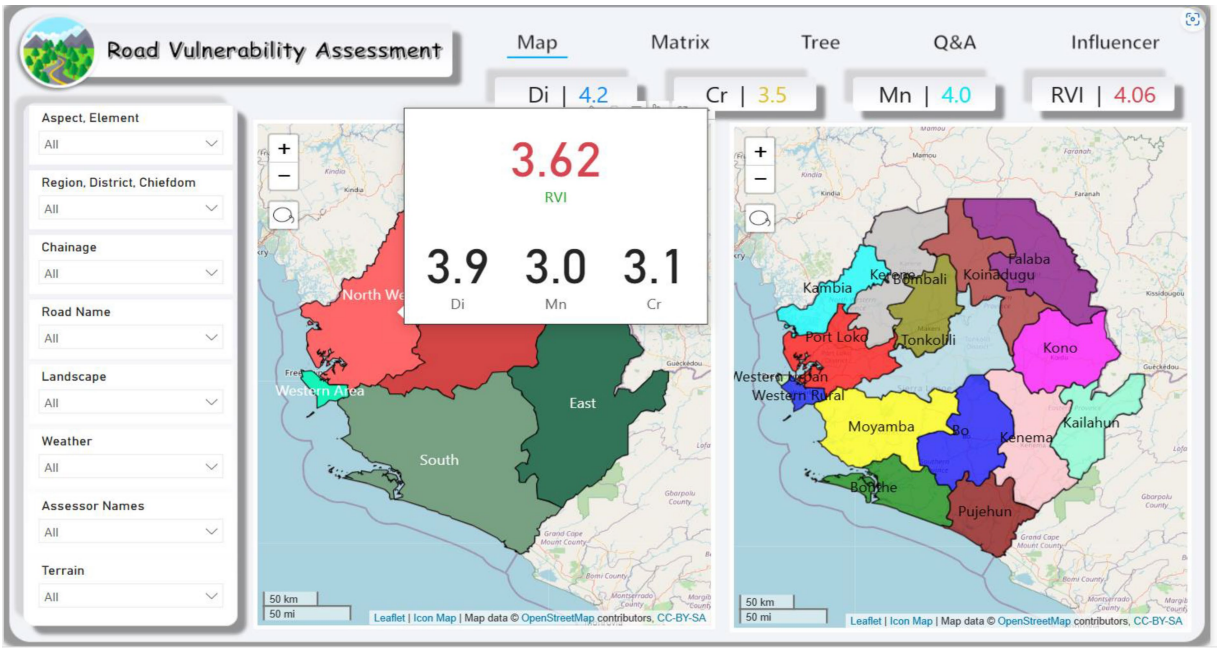


FIGURE 7
Vulnerability assessment results for the Northern Region.

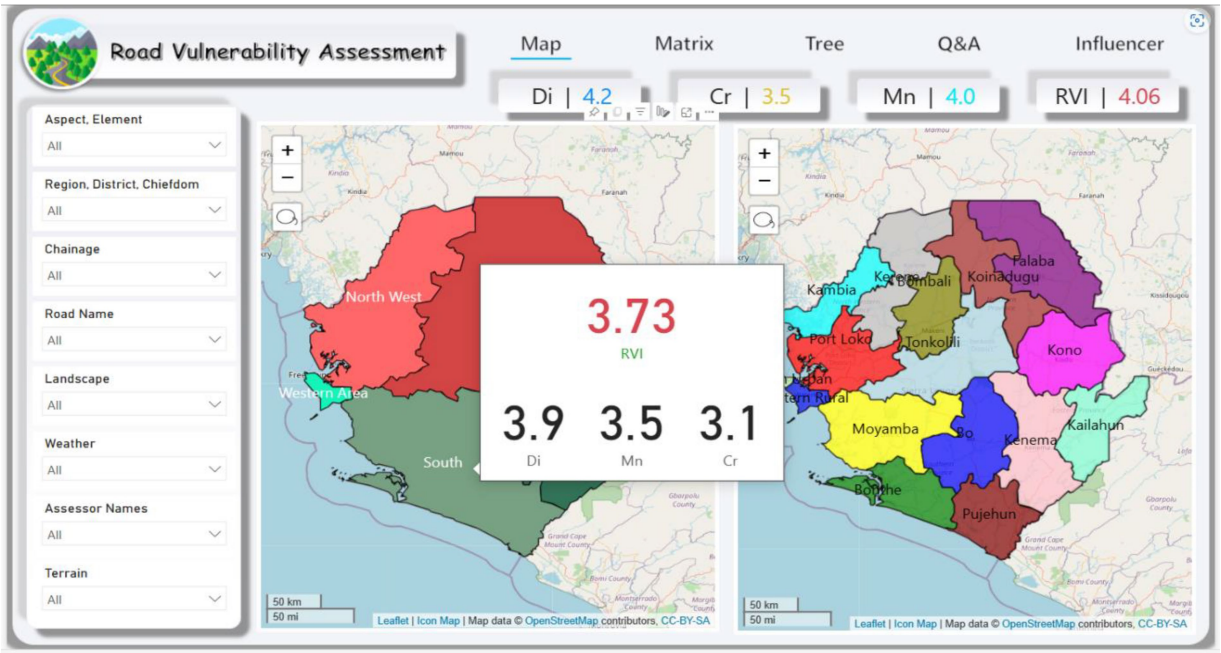


FIGURE 8
Vulnerability assessment results for the Southern Region.

deterioration. The relatively high maintenance score (M_n = 3.4) reflects high maintenance needs, suggesting that either routine maintenance is lacking or is performed below the standard required to ensure climate resilience. A criticality score of 3.3 signals moderate to high socioeconomic importance. These findings highlight the need for sustained, high-quality maintenance to improve road resilience amid climate variability.

In summary, Figures 7–10 present the vulnerability assessment of the case study of unpaved secondary roads across the country. They include analyses of vulnerability indices for the North, South, East, and West regions, using road condition deficiency (D_i), maintenance efficacy (M_n), and criticality (C_r) scores on a 1–5 scale. All regions recorded high RVI values between 3.62 and 3.81, indicating consistently high vulnerability. Severe deterioration is evident from high D_i scores (3.9–4.0), while elevated M_n scores (3.0–3.7) suggest significant maintenance needs; likely due to infrequent or poor-quality interventions. C_r scores (3.1–3.3) point to moderate to high socioeconomic relevance. Overall, these results

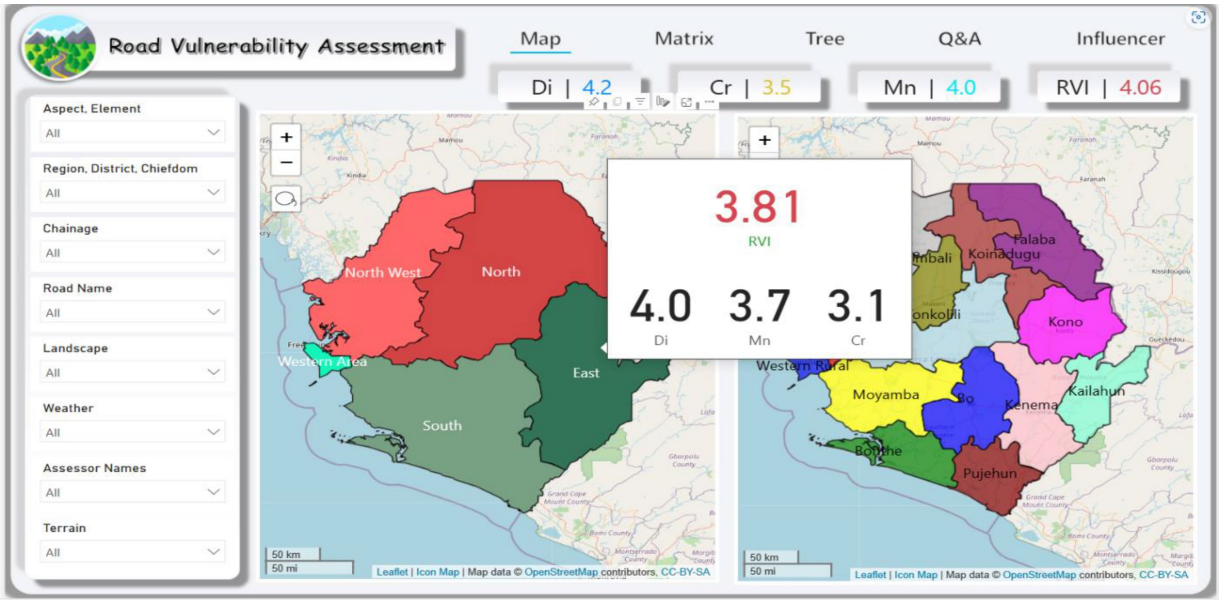


FIGURE 9
Vulnerability assessment results for the Eastern Region.

highlight the combined impact of road conditions, maintenance gaps, and functional importance, emphasizing the need for targeted, climate-resilient road maintenance strategies.

Community inputs on road cut-offs, accident rates, coping measures, and maintenance quality were integrated through the Microsoft Fabric platform, thereby enabling a multi-dimensional analysis and visualization of vulnerability. The results, presented in Figure 5, reveal consistently high vulnerability across all four roads, with RVI values ranging from 3.62 to 3.81 on a 1–5 scale. High D_i scores (3.9–4.0) indicate severe deterioration, while elevated M_n scores (3.0–3.7) reflect substantial maintenance needs stemming from either infrequent or low-quality interventions. Criticality scores (3.1–3.3) demonstrate moderate to high socioeconomic importance. This explicit connection between the framework and the case studies validates the model's ability to capture region-specific vulnerabilities and underscores the urgent need for targeted, climate-resilient maintenance strategies to safeguard these vital road networks. The findings confirm that this context-sensitive, data-light approach delivers accurate, district-level diagnostics of climate vulnerability, making it a scalable and field-responsive alternative to traditional frameworks such as FHWA, ADB, and PIEVC. Additionally, the use of Microsoft Fabric dashboards improved stakeholder engagement and supported informed decision-making, further reinforcing the framework's value for climate-resilient infrastructure planning in low-resource settings.

5 Results

5.1 Results of decades of historical weather-related events

Table 3 presents the output from the EM-DAT and data from national institutions, including the NDMA-SL [Emergency Events Database (EM-DAT) (2023); NDMA-SL (2023)].

These results provide a comprehensive overview of significant weather-related disaster events from 1975 to 2022, indicating that flooding was the most prevalent weather-related event, followed by storms (Table 3). Both flash combined with riverine flooding and storm events were the most prevalent weather-related hazards across all regions, accounting for 51 and 46 of the 110 recorded events, respectively, over the observed period. This high incidence is strongly linked to the influence of large-scale atmospheric drivers, such as the El Niño–Southern Oscillation (ENSO) and the Intertropical Convergence Zone [ITCZ; Intergovernmental Panel on Climate Change (IPCC), 2022]. ENSO events, particularly La Niña phases, are associated with enhanced rainfall in West Africa, whereas seasonal shifts and intensification of the ITCZ can lead to prolonged and intense precipitation episodes [Intergovernmental Panel on Climate Change (IPCC), 2022]. These mechanisms contribute substantially to the observed recurrent flooding, especially in the Western and Southern provinces, where urban runoff and topographic exposure amplify flood risks.

5.2 Results of climate change and variability (30-year meteorological data)

Tables 4–7 present an analysis of meteorological data spanning from 1991 to 2021, including precipitation, temperature, wind speed, and relative humidity (NASA Langley Research Center, 2023).

Key observations from Table 4 reveal the variability in rainfall patterns across districts. All districts showed substantial rainfall variability, with mean annual values ranging from approximately 1,890 mm (Koinadugu) to over 2,600 mm (Western Area). High standard deviations (SDs) indicate significant year-to-year fluctuations. Kendall's tau (τ) values suggest weak to moderate upward trends in most districts, with Pujehun ($\tau = 0.286$, $p = 0.025$) and Bombali ($\tau = 0.260$, $p = 0.041$) showing the most notable increases. These findings highlight regional differences in climate exposure, an

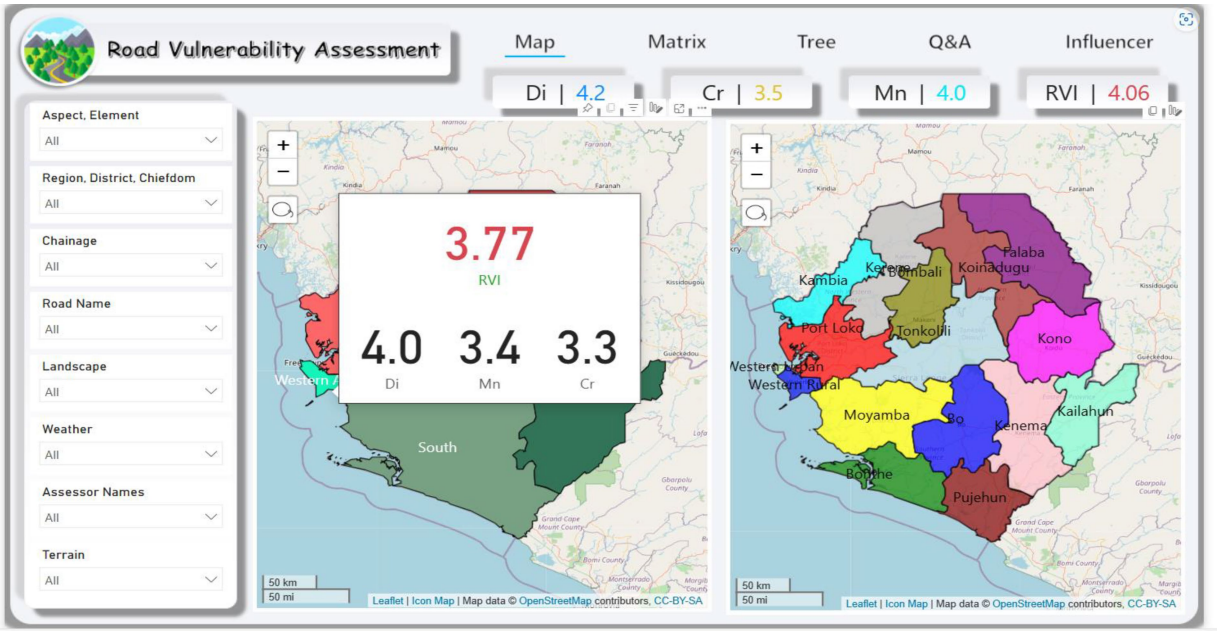


FIGURE 10
Vulnerability assessment results for the Western Region.

TABLE 3 Prominent weather-related events in Sierra Leone from 1975 to 2022.

Regions	Flooding (Flash/ Riverine)	Landslide/ Mudslides	Wildfires	Storms	Total hazards/ region
Western Area	18	3	0	10	31
Northern Province	7	0	1	10	18
Eastern Province	12	0	1	14	27
	14	0	8	12	34
Southern Province	51	3	10	46	110

essential factor in assessing unpaved road vulnerability. To efficiently capture spatial variability and inform the development of a regionally responsive framework for assessing unpaved road vulnerability to climate change, one district per region was selected based on the highest coefficient of rainfall variation (CoV), indicating greater climate stress: Port Loko (North, 50.1%), Pujehun (South, 51.0%), Kenema (East, 49.3%), and Western Rural (West, 50.5%). Additionally, these districts exhibited distinct trend characteristics, including positive Kendall's tau values and meaningful Sen's slopes, with Pujehun showing both the highest CoV and a statistically significant upward trend, thus reinforcing its relevance. This targeted selection ensured analytical clarity, avoided redundancy from similar intra-regional patterns, and enhanced the framework's ability to reflect diverse ecological and geographic climate risks. These findings are consistent with previous studies such as Wadsworth et al. (2019) and Gebrechorkos et al. (2019).

Table 5 presents key descriptive statistics and trend analyses of annual temperature across Sierra Leone's districts over the past 30 years. Mean temperatures ranged from approximately 33.8°C (Bonthe) to 40.5°C (Bombali), with low to moderate interannual variability (SDs between 0.8°C and 2.3°C). Most districts showed weak positive temperature trends, though only Western Rural and Western Urban ($\tau = 0.313$, $p = 0.014$) exhibited statistically significant increases. These results indicate a gradual and spatially uneven warming pattern, with more pronounced changes in the Western region, which represents an important consideration for climate-sensitive infrastructure planning. To capture spatial variability and support a regionally tailored framework for assessing unpaved road vulnerability to temperature-related climate stress, one district per region was selected based on the highest CoV: Port Loko (North, 5.4%), Pujehun (South, 5.5%), Kailahun (East, 6.4%), and Western Rural (West, 2.5%). As presented in Table 6, these districts exhibited distinct trends: Port Loko showed moderate warming, Pujehun a slight cooling trend, Kailahun a stronger warming signal, and Western Rural the most significant warming ($\tau = 0.313$, Sen's slope = 53.488, $p = 0.014$). This strategic selection improved analytical focus, reduced intra-regional redundancy, and strengthened the framework's ability to reflect varied climate risks.

Table 6 summarizes the descriptive statistics and trend analyses of annual wind speed across Sierra Leone's districts from 1991 to 2021. Mean wind speeds ranged from 7.77 m/s in Bonthe to 12.08 m/s in Bombali, with variability levels (SD) between 0.93 m/s and 2.05 m/s. Most districts exhibited weak and statistically insignificant trends. However, Bonthe stood out with a statistically significant increasing

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TABLE 4 Current (past) climatic conditions: annual rainfall in Sierra Leone (1991–2021).

Descriptive statistics of annual rainfall in Sierra Leone (1991–2021) from Mann–Kendall trend test								
Regions	District	Descriptive statistics						
		Min (mm)	Max (mm)	Average (mm)	St. Dev.	Kendall's Tau	$CV = \frac{\sigma}{\mu} x100\%$	*p*-value (Two-tailed)
Northern Region	Koinadugu	395.510	3628.480	1889.944	905.658	0.220	47.9	0.086
	Bombali	427.150	4424.790	2495.325	1087.935	0.260	43.6	0.041
	Tonkolili	427.150	4492.360	2146.440	1057.395	0.233	49.3	0.069
	Port Loko	706.640	5066.810	2072.814	1039.359	0.194	50.1	0.130
	Kambia	727.730	5284.360	2556.269	1101.854	0.202	43.1	0.114
Southern Region	Bo	442.970	4306.880	2064.076	1030.267	0.198	49.9	0.122
	Bonthe	632.810	4133.720	2079.755	919.537	0.228	44.2	0.074
	Moyamba	648.630	5289.260	2383.793	1145.716	0.200	48.1	0.118
	Pujehun	390.230	4256.330	2189.519	1117.404	0.286	51.0	0.025
Eastern Region	Kono	442.970	4101.440	2108.143	1036.490	0.239	49.2	0.062
	Kenema	458.790	4013.090	2046.758	1009.358	0.189	49.3	0.139
	Kailahun	448.240	4074.800	2092.143	1013.136	0.235	48.4	0.066
Western Region	Western Rural	638.090	5980.080	2617.044	1321.470	0.204	50.5	0.110

TABLE 5 Current (past) climatic condition: annual temperature in Sierra Leone (1991–2021).

Descriptive statistics of annual temperature in Sierra Leone (1991–2021)								
Regions	District	Descriptive statistics						
		Min (°C)	Max (°C)	Mean (°C)	St. Dev.	Kendall's Tau	$CV = \frac{\sigma}{\mu} x100\%$	*p*-value (Two-tailed)
Northern Region	Koinadugu	33.000	41.260	37.653	1.882	0.127	5.0	0.324
	Bombali	36.740	42.650	40.547	1.160	0.245	2.9	0.055
	Tonkolili	37.160	42.730	40.486	1.126	0.172	2.8	0.179
	Port Loko	33.470	41.470	36.465	1.983	0.135	5.4	0.292
	Kambia	37.340	43.250	40.242	1.182	0.237	2.9	0.064
Southern Region	Bo	35.390	41.890	39.223	1.466	0.045	3.7	0.734
	Bonthe	31.240	35.370	33.819	0.937	0.112	2.8	0.386
	Moyamba	34.120	40.280	37.195	1.445	0.075	3.9	0.563
	Pujehun	32.260	39.190	35.583	1.949	−0.086	5.5	0.507
Eastern Region	Kono	36.480	41.380	39.095	1.036	0.153	2.6	0.234
	Kenema	35.050	41.400	38.426	1.490	0.123	3.9	0.341
	Kailahun	32.120	40.400	36.158	2.309	0.084	6.4	0.518
Western Region	Western Rural	32.770	36.630	34.180	0.843	0.313	2.5	0.014

trend ($\tau = 0.297$, $p = 0.020$), whereas other districts, such as Bo, Kenema, Port Loko, and Western Rural exhibited weak positive trends, none of which reached statistical significance.

Table 7 presents descriptive statistics and trend analyses of annual relative humidity across Sierra Leone's districts from 1991 to 2021. Mean relative humidity ranged from 72.8% in Bombali to 84.1% in Pujehun, with SDs between 1.38 and 6.48%, indicating low to moderate interannual variability. Most districts exhibited weak negative trends, suggesting slight declines in relative humidity over time. However, none of the trends were statistically significant ($p > 0.05$). The strongest decreasing trends were observed in Kambia ($\tau = -0.175$, $p = 0.174$) and Western Rural ($\tau = -0.132$, $p = 0.308$), while Pujehun was the only district to show a weak positive trend ($\tau = 0.086$, $p = 0.507$). These results suggest a broadly consistent but statistically inconclusive pattern of declining humidity, with potential implications for evapotranspiration, dust generation, and overall moisture conditions relevant to road surface stability and environmental planning.

TABLE 6 Current (past) climatic condition: annual wind speed in Sierra Leone (1991–2021).

Descriptive statistics of annual wind speed in Sierra Leone (1991–2021)								
Regions	District	Descriptive statistics						
		Min (m/s)	Max (m/s)	Mean (m/s)	St. Dev.	Kendall's Tau	$CV = \frac{\sigma}{\mu} x100\%$	*p*-value (Two-tailed)
Northern Region	Koinadugu	10.120	14.290	11.675	1.049	−0.034	9.0	0.799
	Bombali	10.200	15.000	12.083	1.440	0.047	11.9	0.721
	Tonkolili	9.270	19.920	11.612	2.046	0.183	17.6	0.153
	Port Loko	7.310	18.600	10.692	2.034	0.039	19.0	0.773
	Kambia	9.770	19.540	11.328	1.849	0.105	16.3	0.415
Southern Region	Bo	8.440	17.220	10.671	1.968	0.177	18.4	0.169
	Bonthe	6.300	10.530	7.773	0.927	0.297	11.9	0.020
	Moyamba	6.510	12.380	7.933	1.324	0.237	16.7	0.064
	Pujehun	6.460	12.110	7.914	1.274	0.195	16.1	0.130
Eastern Region	Kono	9.270	17.720	11.778	1.572	0.026	13.3	0.852
	Kenema	8.700	18.600	10.873	1.764	0.099	16.2	0.444
	Kailahun	8.700	15.510	10.706	1.467	−0.017	13.7	0.905
Western Region	Western Rural	7.570	12.520	8.994	1.219	0.162	13.5	0.208

TABLE 7 Current (past) climatic condition: annual relative humidity in Sierra Leone (1991–2021).

Descriptive statistics of annual relative humidity in Sierra Leone (1991–2021)								
Regions	District	Descriptive statistics						
		Min (%)	Max (%)	Mean (%)	St. Dev.	Kendall's Tau	$CV = \frac{\sigma}{\mu} x100\%$	*p*-value (Two-tailed)
Northern Region	Koinadugu	56.880	80.310	73.786	6.480	−0.058	8.8	0.658
	Bombali	59.620	78.750	72.825	4.594	−0.086	6.3	0.507
	Tonkolili	66.31	83.12	77.377	3.979	−0.103	5.1	0.424
	Port Loko	74.440	87.310	83.498	3.110	−0.086	3.7	0.507
	Kambia	72.060	84.120	78.624	2.725	−0.175	3.5	0.174
Southern Region	Bo	68.880	86.620	80.600	4.348	−0.101	5.4	0.434
	Bonthe	80.310	85.440	83.505	1.375	−0.030	1.6	0.825
	Moyamba	76.750	87.560	84.045	2.789	−0.056	3.3	0.671
	Pujehun	74.000	88.120	84.149	4.321	0.086	5.1	0.507
Eastern Region	Kono	63.880	81.500	75.922	4.204	−0.084	5.5	0.518
	Kenema	66.690	85.060	79.366	4.764	−0.095	6.0	0.465
	Kailahun	66.690	84.880	80.101	5.199	−0.078	6.5	0.551
Western Region	Western Rural	79.880	85.750	83.463	1.458	−0.132	1.7	0.308

To develop a regionally responsive climate risk framework for unpaved roads, one district per region was selected based on the highest relative humidity variability: Koinadugu (North, SD = 6.48%), Pujehun (South, 4.32%), Kailahun (East, 5.20%), and Western Rural (West, 1.46%). These districts show the largest interannual humidity fluctuations (1991–2021), reflecting potential moisture stress across ecological zones. Kendall's tau trend analysis revealed weak, statistically insignificant changes, with negative values in Koinadugu, Kailahun, and Western Rural and a slight positive trend in Pujehun ($\tau = 0.086$, $p = 0.507$). Though not significant, selecting these districts captures spatial variability critical for assessing moisture-related vulnerability in unpaved roads. Mean relative humidity in the selected districts ranged from 73.8% (Koinadugu) to 84.1% (Pujehun), generally sufficient to support soil moisture retention. However, variability and slight declining trends, particularly in the northern and eastern districts, suggest periods of drying that can increase dust,

reduce surface cohesion, and accelerate road deterioration. These results highlight relative humidity as a critical factor in climate vulnerability assessments for unpaved roads.

5.3 Results of predicted climate change and variability (exposure analysis)

This section presents the results of the forecast exposure to climate change and variability experienced by unpaved secondary roads in Sierra Leone. The exposure analysis of identified climate hazards under future climatic conditions was conducted using statistical time series ARIMA modeling for near-term point forecasts. The forecast covered 10 years and considered the economic outlook and the design life of unpaved secondary. The results are presented in Tables 8–11 for a forecasted period of 2021 to 2031.

As presented in Table 8, the 10-year ARIMA rainfall forecasts (2021–2031) for the selected vulnerable districts Port Loko, Pujehun, Kenema, and Western Rural revealed marked spatial variability and significant uncertainty, particularly in Western Rural, which is projected to receive the highest mean annual rainfall (4,118.82 mm) with an exceptionally wide 95% confidence interval (CI) of 896.13–13,160.13 mm, signaling a high likelihood of extreme rainfall events. In addition, the other districts, Port Loko (3,786.89 mm), Pujehun (3,418.58 mm), and Kenema (3,380.88 mm), exhibited considerable interannual fluctuations, with forecast ranges showing early-year peaks gradually stabilizing toward 2031. These rainfall projections feed directly into the unpaved road vulnerability assessment framework by identifying districts most exposed to climate-induced stressors such as erosion, surface degradation, and drainage failure. The incorporation of forecast trends and uncertainty enabled more region-specific and forward-looking adaptation strategies for enhancing the resilience of road infrastructure under future climate variability.

As shown in Table 9, the 10-year ARIMA temperature forecasts (2021–2031) for Port Loko, Pujehun, Kenema, and Western Rural revealed modest spatial variability, which was less pronounced than that for rainfall. Port Loko shows the greatest fluctuation, with projected temperatures ranging from 36.43°C to 38.09°C, above its baseline of 36.47°C. Pujehun ranged from 34.58°C to 35.51°C (baseline: 35.58°C), whereas Kenema's forecast narrowed to 36.07°C–36.11°C, slightly below its 36.16°C baseline. Western Rural remained stable at 34.16°C, slightly lower than its 34.18°C baseline, suggesting minimal change or slight cooling. These projections, with 95% CIs, inform the vulnerability assessment by identifying potential temperature-related impacts, such as cracking and material degradation, on unpaved roads. The overall trend indicates a gradual increase in mean surface temperatures across the country, supported by both observational and model-forecasted data, which aligns with increased temperature projections for West African regions (USAID, 2017; Stoerk et al., 2018).

As shown in Table 10, the 10-year ARIMA wind speed forecasts (2021–2031) for Port Loko, Pujehun, Kenema, and Western Rural indicated relatively low spatial variability compared to that of rainfall and temperature. In Port Loko (Northern region), projected mean annual wind speeds fluctuated around 10.40 m/s, which is slightly below the historical baseline of 10.69 m/s. Pujehun (Southern region) forecasts ranged near 7.77 m/s, which is marginally lower than the baseline of 7.91 m/s. Kenema (Eastern region) showed a projected mean of 11.36 m/s, slightly above its historical baseline of 10.87 m/s. In Western Rural, the forecast stabilized at 8.86 m/s, which is nearly equal to the 8.90 m/s baseline. As with the rainfall and temperature models, the ARIMA wind speed forecasts included 95% CIs for various return periods. These projections are critical for the road vulnerability assessment framework, particularly in evaluating the potential influence of wind-driven erosion, dust dispersion, and structural impacts on exposed road surfaces and drainage systems.

As presented in Table 11, the 10-year ARIMA relative humidity forecasts (2021–2031) for Port Loko, Bo, Kailahun, and Western Area show minimal spatial variability compared to that of the other climate parameters. In Port Loko (Northern region), the projected mean annual relative humidity was approximately 73.75%, closely aligning with the historical baseline of 73.79%. Bo (Southern region) exhibited forecasts ranging from 80.43 to 81.33%, which was similar to the baseline mean of 80.60%. In Kailahun (Eastern region), the projected values ranged from 80.02 to 82.73%, which were slightly above the baseline of 80.10%. For the Western Area, the forecasts remained stable between 83.46 and 83.63%, consistent with the baseline of 83.46%. As with the temperature, rainfall, and wind speed models, the ARIMA relative humidity forecasts included 95% CIs across various return periods. These projections are vital for informing the road vulnerability assessment framework, particularly in evaluating moisture-related impacts such as subgrade weakening, surface slipperiness, and the potential for material degradation in high-humidity environments.

6 Discussion

As presented in Table 3, the consistent occurrence of at least 23 weather-related disasters per decade underscores the frequency and intensity of climatic events in Sierra Leone and presents significant

TABLE 8 Rainfall forecast indices for selected vulnerable districts in Sierra Leone.

Region	District	Forecasted mean annual rainfall (mm)	95% confidence interval	
			Lower-bound forecasted mean annual rainfall (mm)	Higher-bound forecasted mean annual rainfall (mm)
North	Port Loko	3786.887	781.9190	7338.009
South	Pujehun	3418.578	374.8251	6249.010
East	Kenema	3380.879	501.6305	7036.712
Western	Western Rural	4118.823	896.1296	13160.125

TABLE 9 Temperature forecast indices for selected vulnerable districts in Sierra Leone.

Region	District	Forecasted mean annual temperature (°C)	95% confidence interval	
			Lower-bound forecasted mean annual temperature (°C)	Higher-bound forecasted mean annual temperature (°C)
North	Port Loko	36.42843	33.02086	41.32809
South	Pujehun	35.50596	31.33038	39.23472
East	Kailahun	36.10734	31.14497	40.46571
Western	Western Rural	34.1609	32.60697	35.86183

TABLE 10 Wind speed projection indices for selected vulnerable districts in Sierra Leone.

Region	District	Forecasted mean annual wind speed (m/s)	95% confidence interval	
			Lower-bound forecasted mean annual wind speed (m/s)	Higher-bound forecasted mean annual wind speed (m/s)
North	Port Loko	10.40005	7.840145	15.20538
South	Pujehun	7.765299	6.178569	10.35813
East	Kenema	11.36107	8.911373	15.5091
Western	Western Rural	8.858227	7.129513	11.6049

TABLE 11 Relative humidity projection indices for selected vulnerable districts in Sierra Leone.

Region	District	Forecasted mean annual R. humidity (%)	95% confidence interval	
			Lower-bound forecasted mean annual R. humidity (%)	Higher-bound forecasted mean annual R. humidity (%)
North	Koinadugu	73.74947	60.64711	91.93520
South	Bo	81.32985	72.10637	90.79701
East	Kailahun	82.72972	70.53903	94.43439
Western	Western Rural	83.63493	80.50853	86.31597

implications for the resilience of unpaved roads. Rainfall, particularly in terms of duration and intensity, is a primary driver of road surface erosion (Zhao et al., 2021). Over the past four decades, the rise in intense single-day rainfall events has led to frequent flooding—most notably in the Western and Southern regions, which recorded 18 and 14 flood events respectively, likely accelerating the degradation of unpaved roads. Soil erosion is influenced by factors such as soil type, clay content, plasticity, particle size distribution, surface compaction, traffic load, and speed (Ngezahayo et al., 2019). However, due to logistical and data limitations, detailed soil attribute data for the study area were unavailable, necessitating the use of proxy indicators. The underlying geology, dominated by weathered granitic, metamorphic, and sedimentary rocks, has a high erodibility potential (Jalloh et al., 2013), and when combined with unbound road surfaces, unlined drainage, and vulnerable geometry, the erosion risk reaches a high level. Increased precipitation-related hazards such as flooding and storms further exacerbate this risk. Observed data indicate that rainfall has increased across all regions of Sierra Leone, a trend that may be linked to the ENSO phenomenon, which shifts the ITCZ and alters rainfall distribution patterns (Timmermann et al., 2018). For the road sector, higher rainfall levels intensify erosion and sedimentation, washing away surface materials and embankments, narrowing and lowering roadways, and depositing debris in drainage systems, thereby reducing their capacity and increasing flood risks (Zhang et al., 2019). In addition, such increases weaken the strength and stiffness of supporting soil layers, making roads more susceptible to deformation, rutting, cracking, and potholing under traffic loads. These impacts reduce ride quality, safety, and service life while increasing the frequency and cost of maintenance interventions.

The trend analysis of 30-year meteorological rainfall data and 10-year forecasted rainfall, as revealed by the Mann-Kendall trend tests and statistical time series ARIMA modeling (Tables 4, 8, respectively), revealed an overall pattern of increasing rainfall variability across all regions. These findings are consistent with previous research conducted in other Sub-Saharan African (SSA) regions, such as by Shongwe et al. (2011) and Endris et al. (2013). Shongwe et al. (2011) utilized RCM simulations to evaluate future changes in rainfall and temperature across southern Africa. They projected a 5 to 20% decrease in annual mean rainfall by the end of the 21st century, with particularly pronounced decreases in the Western and Southern regions, accompanied by increased rainfall variability and extremes, leading to more frequent and intense droughts and floods. Similarly, Endris et al. (2013) employed statistical downscaling techniques to analyze future changes in rainfall and

temperature over East Africa using global climate model outputs. They forecasted a 10 to 15% decline in annual mean rainfall by the end of the 21st century, primarily in the northern and eastern regions, alongside alterations in rainfall seasonality and variability, resulting in more erratic and unpredictable patterns. The forecasted increase in rainfall variability, combined with more frequent and intense rain events, poses significant challenges for unpaved roads, leading to accelerated erosion, higher flood risks, and road surface deterioration. These issues heighten safety concerns, escalate maintenance expenses, impede access to essential services, and threaten the long-term viability of unpaved road networks, underscoring the importance of proactive resilience-building strategies and infrastructure investments.

In the case of temperature, the observed upward trends across Sierra Leone, as indicated in Table 5, are consistent with regional climate dynamics reported by Solomon et al. (2022) in their study on the Mano River Union (MRU) sub-region, which may have significant implications for unpaved secondary roads, which are constructed with unbound granular materials. Similar findings from the literature indicate that elevated temperatures contribute to increased evaporation rates, which reduce the moisture content essential for maintaining the cohesion and structural integrity of such road surfaces (de Abreu et al., 2022; Solomon et al., 2022). As a result, roads become increasingly dusty, brittle, and prone to raveling and surface erosion under both climatic stress and traffic loading. The drying out of surface layers also weakens the bearing capacity of the road, making it vulnerable to deformation, cracking, and accelerated deterioration. These temperature-induced vulnerabilities underscore the need for adaptive design standards and improved maintenance strategies to ensure the resilience of rural road networks in Sierra Leone and across the MRU region in the face of rising climate stressors.

The 10-year forecasts, as shown in Table 9, indicate an increase in temperature across all the regions in the country, which is consistent with Solomon et al. (2022), who identified Sierra Leone as experiencing significant climatic variability within the Mano River Region. The forecast results are also consistent with continental projections. James and Washington (2013) predicted a 1.5°C to 5°C rise in mean annual temperature across Africa by the end of the century, with the greatest warming in the north and south and more frequent extremes. Engelbrecht et al. (2015) projected a 2°C to 6°C increase in southern Africa, particularly in interior and Western regions, with changes in seasonality. Lennard et al. (2018) estimated a 1.5°C to 4.5°C rise in East Africa, with peak warming in northern and eastern areas and a longer, earlier warm season. Such trends underscore the need to integrate climate forecasts into infrastructure planning, particularly for climate-sensitive sectors such as transport. Elevated temperatures pose substantial risks to unpaved road infrastructure in Sierra Leone by accelerating surface degradation through increased evaporation, reduced soil moisture, dust generation, and heightened vulnerability to erosion and siltation during heavy rainfall (Le Roux et al., 2019b; Le Roux et al., 2019a). These impacts are likely to increase maintenance demands, compromise structural integrity, disrupt transport services, and contribute to environmental degradation (Mark Partington et al., 2018). Therefore, incorporating forecasted climate variables such as temperature into a vulnerability assessment framework is essential for identifying high-risk road segments and informing the design, maintenance, and adaptation of resilient road infrastructure under changing climate conditions.

For wind speed, the trend analysis (Table 6) revealed a weak to moderate increase across all the districts over the observed period, with Western Rural exhibiting the strongest signal ($\tau = 0.162$, $p = 0.208$). Although the trends were not statistically significant, their inclusion was critical for capturing spatial differences in wind-related climate stress, reducing intra-regional redundancy, and improving the framework's sensitivity to localized climatic dynamics. Mean wind speeds across the selected districts ranged from 8 m/s to over 12 m/s, indicating moderate to strong conditions on the Beaufort scale, sufficient to sway branches and raise dust as reported by Suomi and Vihma (2018). These findings underscore wind exposure as a relevant stressor, enhancing the climate vulnerability framework for unpaved road planning and resilience. Additionally, the findings align with those of similar studies in sub-Saharan Africa. For example, Libanda (2023) observed seasonal wind speed variations in Zambia, with peak values in August–September, whereas Moses and Parida (2016) reported consistently strong wind speeds (13.80–21.69 m/s) in Botswana, supporting the variability of wind energy in the region. These comparisons suggest that observed wind speed patterns in Sierra Leone are consistent with broader regional trends. The increasing variability in wind speed over time may be linked to factors such as climate change, topography, and land use changes. Shifts in sea surface temperatures and atmospheric pressure gradients (Hayes et al., 1989). Sierra Leone's diverse terrain, including coastal marsh, interior plain, plateau and mountainous areas, also contributes to localized variations in wind speed and direction (Amara et al., 2020). Moreover, land cover changes, particularly deforestation and urban expansion, may have reduced surface roughness and altered wind flow dynamics (Gbanie et al., 2018). These changes have practical implications for unpaved roads, as stronger winds can accelerate surface erosion, displace loose materials, increase maintenance demands, reduce visibility, and pose safety and health risks due to dust dispersion (Cardozo and Sánchez, 2019; de Abreu et al., 2022).

The 10-year forecasts show strong winds and moderate gales can cause significant damage to the ecosystem, aligning with findings from other studies, such as Suomi and Vihma (2018). These forecasts are consistent with the findings of Solomon et al. (2022), who investigated climatic variabilities in the MRU regions and their implications on socioeconomic development sectors. The heightened forecasted wind speed, particularly exceeding thresholds for wind erosion in all regions, poses significant ramifications for unpaved roads. High wind speeds elevate erosion risk, potentially leading to surface instability and degradation, while also increasing dust generation, creating hazardous driving conditions and health risks for nearby communities. These challenges necessitate proactive measures, including erosion control, improved road design, and regular maintenance, to mitigate adverse impacts and enhance road resilience.

For relative humidity, the observed decline in trends (Table 7) is consistent with prior studies in sub-Saharan Africa. Ndebele-Murisa et al. (2011) reported a decrease of 0.8% per decade over Lake Kariba, alongside increased evaporation, while Nicholson et al. (2018) found a continental decline of 0.4% per decade, particularly pronounced in the Sahel and Southern Africa. These regional trends mirror the slight but consistent decreases in relative humidity seen in Sierra Leone over the observed period. This decline is likely driven by changes in atmospheric circulation, moisture transport, and land surface feedbacks (Nicholson et al., 2018), although it could be driven by variations in temperature, wind speed, and cloud cover

(Ndebele-murisa et al., 2011). Reduced humidity has direct implications for unpaved roads: lower moisture levels decrease cohesion in unbound granular materials such as gravel and sand, leading to increased dust emission, surface erosion, and deterioration (Lera and Kuleno, 2020). Soils in unpaved roads may also dry, contract, and crack, undermining load-bearing capacity and increasing vulnerability to deformation under traffic. These findings emphasize the importance of incorporating relative humidity trends into vulnerability assessments for unpaved road infrastructure.

The forecast from the statistical time series ARIMA-based model (Table 11) is consistent with regional climate studies across the MRU. Solomon et al. (2022) observed significant climatic variability within the MRU region, highlighting shifts in relative humidity as a key concern for Sierra Leone's climate future. These projections are further supported by Abatan et al. (2016), who used global and regional climate models to estimate a 0.5–2.5% increase in annual mean relative humidity across West Africa by the end of the 21st century, particularly in coastal and central zones, driven by evolving monsoon circulation, moisture convergence, and land-atmosphere feedbacks. In Sierra Leone, the near-term ARIMA forecasts reveal modest variability in relative humidity, which may significantly affect unpaved road infrastructure. Humidity fluctuations can reduce surface cohesion, intensify erosion, and accelerate material degradation. These findings highlight the importance of incorporating relative humidity projections into road vulnerability assessments and maintenance planning frameworks to enhance the climate resilience of unpaved roads.

The climate trend analysis (1991–2021) revealed significant spatial and temporal variability in rainfall, temperature, wind speed, and relative humidity across Sierra Leone, with the most climate-variable districts Port Loko, Pujehun, Kailahun, and Western Rural facing critical stressors, such as erosion, soil drying, and dust generation that undermine unpaved road performance. Building on this data-driven foundation, the proposed stakeholder-centered framework actively engages communities along the road and other key stakeholders to capture their perspectives on climate change and variability, as well as the implications for unpaved roads in their areas. This inclusive approach enriches the technical analysis with local knowledge, ensuring that adaptation strategies reflect on-the-ground realities. The framework assesses the current vulnerability of selected unpaved secondary roads, indicating high risks of accelerated deterioration without targeted adaptation. The 10-year climate forecast further projects an increase in the frequency and intensity of these stressors, heightening the urgency for proactive measures. Uniquely in Sub-Saharan Africa, this study connects climate variability to geotechnical failure mechanisms, attributing observed and projected changes to drivers such as ENSO, topography, and land use. The resulting cost-effective, user-friendly tool integrates historical trends, forecasted climate data, engineering insights, and community perspectives to support regionally responsive adaptation and maintenance strategies for building climate-resilient unpaved road networks.

7 Conclusion

7.1 Practical implications

This research addresses limitations of existing climate risk assessment frameworks, such as those by the FHWA, Asian Development Bank, and World Bank, which often rely on proprietary software and high-end computing infrastructure, making them suitable for Sierra Leone's data-scarce, capacity-limited, and topographically complex environment. In response, a pioneering, IPCC-endorsed, five-phase climate vulnerability assessment framework was developed, tailored to unpaved secondary roads in resource-constrained settings. The framework integrates environmental, infrastructural, socioeconomic, and community perception indicators and combines GPS-enabled field data collection, spatial analysis, and short-term climate forecasting using open-source tools, including QGIS, QField, KoBoToolbox, and Microsoft Power BI. Analysis of historical, current, and projected climate conditions highlighted significant regional disparities in the hazards, with vulnerability indices for four assessed roads ranging from 3 to 4, indicating high susceptibility to climate impacts. Visualization through maps, charts, and dashboards strengthens decision-making, while the case studies confirm the framework's practicality and scalability. By embedding community perspectives, applying statistical methods such as ARIMA and Mann-Kendall tests, and linking climate variability to geotechnical failure mechanisms, the framework offers a cost-effective, participatory, and transferable approach for prioritizing maintenance, guiding targeted adaptation, and advancing climate-resilient infrastructure planning in Sierra Leone and similar contexts across the Global South.

7.2 Policy implications

This research recommends that the SLRA adopt the proposed climate risk and vulnerability assessment framework to strengthen the resilience of the country's unpaved secondary roads. The framework is practical, cost-effective, and adaptable to Sierra Leone's diverse terrains, and it also addresses capacity gaps, enhances data collection, and fosters community participation to support informed decision-making and adaptation planning. Aligned with the National Adaptation Plan, Nationally Determined Contributions, and SDGs 9, 11, and 13, the framework enables policymakers to design climate-resilient road networks that safeguard rural connectivity, economic activity, and disaster preparedness. Beyond Sierra Leone, the framework offers a scalable and replicable model for the Global South, particularly sub-Saharan Africa, where similar climatic, infrastructural, and capacity challenges exist. By integrating scientific analysis with community knowledge and policy priorities, it provides a transferable template for embedding locally grounded climate considerations into transport strategies, advancing resilient infrastructure, promoting equitable climate adaptation, and supporting sustainable economic development.

7.3 Strengths and weaknesses

This study presents a flexible and practical framework for assessing climate risk and vulnerability in Sierra Leone's unpaved secondary roads. Key strengths include its real-world applicability, as demonstrated through case studies; alignment with national policy priorities; cost-effectiveness through the use of open-source technologies; and holistic approach that integrates technical, environmental, and socio-economic factors. Its scalability further positions it as a potential model for application in similar global contexts. However, this study also acknowledges several limitations,

including the absence of direct stakeholder validation, challenges in data accessibility, resource constraints, a narrow focus limited to four case studies, limited community engagement, and untested scalability. Future research should address these gaps by incorporating stakeholder validation, enhancing community involvement, testing scalability across diverse terrains, and improving data availability and resource support.

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

PK: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft. YT: Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Validation, Writing – review & editing. FB-A: Conceptualization, Data curation, Project administration, Resources, Software, Supervision, Validation, Writing – review & editing. DO: Conceptualization, Project administration, Resources, Supervision, Validation, Writing – review & editing.

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Conflict of interest

The authors declare that this study received funding from the World Bank. The World Bank had no involvement in the study design, data collection, analysis, interpretation, writing of the article, or the decision to submit it for publication.

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Temporal variation and environmental drivers of soil heat flux and surface solar radiation in the northern Qinling foothills

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Introduction: Based on 2021–2023 meteorological data from the northern Qinling foothills.
Methods: This study reveals spatiotemporal variations in soil heat flux (G) and surface solar radiation and their correlations with environmental factors.
Results: Results show soil heat flux (G), measured at 5 cm depth, exhibits a distinct 'S'-shaped diurnal pattern and seasonal differences, with correlations with surface radiation of R^2 = 0.85 (daily scale) and 0.92 (monthly scale) ($p < 0.001$), respectively. Environmental temperature, soil moisture, and wind speed are significantly positively correlated with G (r = 0.72, 0.24, 0.27, respectively; $p < 0.001$), while rainfall and atmospheric pressure show negative correlations (r = −0.27, −0.70).
Discussion: These findings provide data support for studying energy exchange in regional soil-vegetation-atmosphere systems.

KEYWORDS

northern foothills of the Qinling Mountains, surface solar radiation, soil heat flux, seasonal variation characteristics, environmental factors

1 Introduction

The Qinling Mountains, a temperate-subtropical transition zone, are ecologically and geographically significant in disciplines such as ecology, geography, and soil and water conservation (Jiang et al., 2013). As a key geographic boundary in China's mid-latitude region, the Qinling Mountains are a sensitive area for regional responses to and adaptations to global changes. Their unique geographic location makes them particularly valuable for research in geography, forest hydrology, and ecology. Most studies on climate change and environmental effects in the region have focused on the spatial and temporal changes in conventional hydrometeorological elements, such as temperature, precipitation, drought indicators and runoff, along with their interrelationships. Climate change research has also emphasized changes in vegetation cover, species diversity (animal and plant), and soil and water conservation. As the main driving force of terrestrial ecosystems and a crucial energy source for human activities, solar radiation directly affects the photosynthetically active radiation of vegetation and indirectly affects vegetation evaporation and soil moisture content. Soil, as the natural environment for plant survival, is a vital component of ecosystems and a key medium for energy exchange; Soil heat flux is a key component of the surface heat balance and an important physical parameter characterizing soil thermal conditions. This component

directly influences soil temperature changes and is a crucial factor in the energy balance equation of forest ecosystems, substantially affecting the system's energy closure (Jiang et al., 2013). Although soil heat flux may be numerically small in observations, this component is essential for evaluating energy closure at smaller time scales. Furthermore, changes in soil heat flux can have a substantial effect on the root uptake capacity of crops (Hurd and Craves, 1985). Wang Guosheng et al. analyzed the variation characteristics of each radiation flux and surface albedo at different time scales and under different weather conditions on the East Pamir Plateau (Wang et al., 2023). In addition, other scholars have also deeply analyzed the characteristics of the energy flat component of the subsurface of deserts (Chang et al., 2021; Li et al., 2022a; Cao et al., 2021), grasslands (Zhang et al., 2020; Li et al., 2021; Xiao et al., 2011) and farmlands (Chen et al., 2016; Wu et al., 2007). While numerous studies have focused on changes in rainfall and temperature in the Qinling regionexploring the spatial and temporal patterns and dynamics of climate, temperature, and rainfall in the northern and southern foothills of the Qinling Mountains, the impact of land heat flux on climate, energy balance, and vegetation types in the region is also substantial (Li et al., 2012; Bai, et al., 2012). For example, Sun Cheng et al. highlighted the importance of soil temperature (and changes in soil heat flux) for the emergence of Moso bamboo (Sun et al., 2013). Specifically, between March and May each year, when the soil temperature reaches 13 °C for a period of 10 days, Moso bamboo shoots begin to emerge from the ground.

Numerous studies have been conducted on surface solar radiation and soil heat fluxes in the regions such as the Tibetan Plateau (Ci et al., 2013; Gu et al., 2018; Zhang et al., 2021; Ma et al., 2005), southern subtropical mixed coniferous and broad forests (Wang et al., 2005), and the Minqin Desert area (Wang et al., 2004). However, studies on surface solar radiation and soil heat fluxes in the Qinling region are relatively limited. Soil heat flux (G) is defined as vertical heat transfer ($W{\cdot}m^{-2}$), with positive values indicating downward flow (heat sink) and negative values upward release (heat source). Surface solar radiation refers to total solar irradiance ($W{\cdot}m^{-2}$).

The seasonal dynamics of soil heat flux represent a critical component of surface energy partitioning and regional climate regulation. This is particularly true in ecologically sensitive areas with complex topography and distinct climatic transitions, such as the northern foothills of the Qinling Mountains (Qin et al., 2022). However, significant research gaps persist regarding the mechanisms by which soil heat flux variations regulate energy balance in this region. While existing studies have revealed universal patterns such as soil thermal lag effects (Zhang et al., 2011) and energy suppression during freezing periods, local observational data specific to the Qinling foothills remain scarce. As a product of coupled water-heat processes, soil heat flux dynamics are governed by the synergistic interactions of temperature, precipitation, wind speed, and biological activities. However, the mechanisms underlying these multi-factor interactions—and their specific impacts in the northern Qinling foothills—remain unclear. For example, precipitation events may modulate heat diffusion efficiency by altering soil water content, while wind disturbances could accelerate surface soil evaporative cooling, creating a competitive relationship with solar radiation-driven warming effects (Yang D. et al., 2024).

This study takes the northern foothills of the Qinling Mountains as the research object, continuously monitors the meteorological and soil data of this region from 2021 to 2023, and collates and analyzes the data. The 2021–2023 dataset includes normal climatic conditions and extreme events (such as 166 mm precipitation in August 2023), providing a robust basis for analyzing the responses of soil heat flux to diverse environmental stresses. By integrating multi-source observations and model simulations (Xu et al., 2021), this study focuses on the macro-scale impacts of soil heat flux on energy balance at seasonal scales, and then reveals micro-scale driving mechanisms from the perspective of multi-factor interactions. These two aspects form a progressive "phenomenon-mechanism" relationship. For the first time in the northern Qinling foothills, this research quantifies the coupling between soil heat flux and surface solar radiation across different time scales, as well as the mutual influence coefficients among environmental factors, soil heat flux, and surface solar radiation. The goal is to uncover the controls of regional climate and soil properties on energy exchange, provide multi-dimensional insights for studying energy cycles in mountain ecosystems, and offer a scientific basis for the sustainable management of mountain ecosystems.

2 Materials and methods

2.1 Experimental site

The test area is located at the Qinling Field Monitoring Center Station (34° 8′31 "E, 107° 53′24" N) of the Key Laboratory of Degraded and Unutilized Land Remediation of the Ministry of Natural Resources, at an elevation of 605.8 m. The study site in Meixian County, Baoji City, Shaanxi Province, on the northern side of the main peak of the Qinling Mountains, Taibai. Meixian County features loessial soils and a mixed deciduous broadleaf forest ecosystem, with an average annual temperature of 12.8 °C and precipitation of 581.6 mm, characteristic of warm temperate continental monsoon climates. This area is situated Meixian County, Baoji City, Shaanxi Province, on the northern side of the main peak of the Qinling Mountains, Taibai. The region falls under a warm temperate continental monsoon climate with characteristics of rain and heat in the same season. This area is characterized by large diurnal temperature variation, high rainfall, strong evaporation, and dryness; it also has an average annual temperature of 12.8 °C and receives an average precipitation of 581.6 mm per year.

Due to the influence of different surface covers on soil thermal conductivity and heat flux (Li et al., 2008; Fu et al., 2017), to eliminate potential impacts of vegetation coverage and micro-topography on heat flux measurements at the experimental site, this study adopted a bare ground treatment and established the experimental area in a relatively flat region.

2.2 Test facilities

The data source is the SMR-CR series environmental weather station at the Qinling Field Testing Center Station, established in

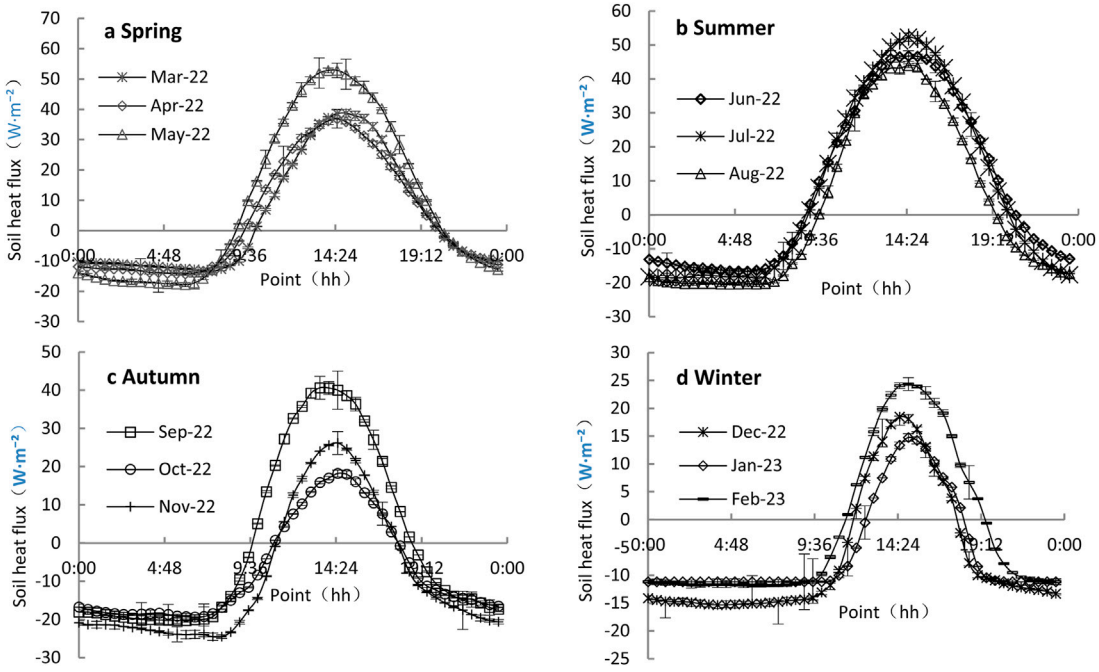


FIGURE 1
Daily variation patterns of soil heat flux in different seasons: **(a)** Spring, **(b)** Summer, **(c)** Autumn, and **(d)** Winter. Figure caption: Error bars represent standard deviation (n=3 years for monthly data, n=12 months for seasonal data).

May 2017 and put into operation thereafter. The station is equipped with CSI's CR series data collector as the core, which connects various meteorological and ecological environmental sensors, including those for wind speed, wind direction, air temperature, air humidity, atmospheric pressure, rainfall (snow), surface solar radiation, and soil temperature, humidity, and salinity. The system is supported by the necessary chassis, brackets, and power supply (solar/AC) to form a complete, unattended field environmental monitoring station. The data collector serves as the core of the system, controlling its operation and storing raw data files for researchers to access and analyze.

The weather station is equipped with a CR1000 data collector from CSI, a TE525MM tipping bucket rain gauge (capable of measuring precipitation increments of 0.1 mm), a CMP3 total radiation meter, a Hydya Probe II soil temperature, moisture, and salinity probe, and two HFP01 soil heat flux panels. The two HFP01 soil heat flux plates used have a measurement range of −200 to 200 W/m^2, a measurement precision of ±5% within the rated measurement range, a response time of less than 1 s, and adopt the thermocouple-based measurement principle, which can accurately capture the flux changes during the soil heat transfer process. Only the facilities relevant to the data presented in this paper are listed here.

2.3 Test methods

The experimental data, including surface solar radiation, rainfall, ambient temperature, soil temperature, and soil heat flux, were obtained from the environmental weather station, with data collected once every 30 min.

Daily statistics were calculated by averaging all data collected within a single day, and monthly statistics were derived by averaging the daily statistics.

Data Quality Control: Raw data were processed using the following steps: (1) Outliers were identified and removed using the 3σ criterion, with missing values imputed via linear interpolation based on adjacent measurements. (2) Soil heat flux sensors (HFP01) were buried at 5 cm depth to minimize surface disturbance and capture shallow soil flux relevant to vegetation root zones, with calibration performed annually using a heat flux standard (±5% accuracy). (3) For multivariate analysis, collinearity was assessed via variance inflation factor (VIF) values (<2, indicating no severe collinearity), and Pearson correlation assumptions (normality, linearity) were verified using Q-Q plots and scatter diagrams.

Total missing rate of 3-year (2020–2022) data was ~3.2%; soil moisture had the highest missing proportion (1.5%) due to temporary sensor malfunctions, while other factors had <1% missing rate. Missing values were evenly distributed across seasons (3.0% spring, 3.5% summer, 3.1% autumn, 3.2% winter), with no concentration in extreme weather. Only 1-day missing data occurred in September 2021 (sensor calibration), accounting for 0.3% of total missing data. Using 2021 (2.1% missing rate) as the validation period: compared correlation coefficients between "interpolated data" and "original complete data—max daily difference = 0.02, monthly differences <0.01, indicating negligible impact of linear interpolation on key results.

The data were processed and plotted using Excel, and statistical analysis was performed using SPSS 19 software and Origin 2024.

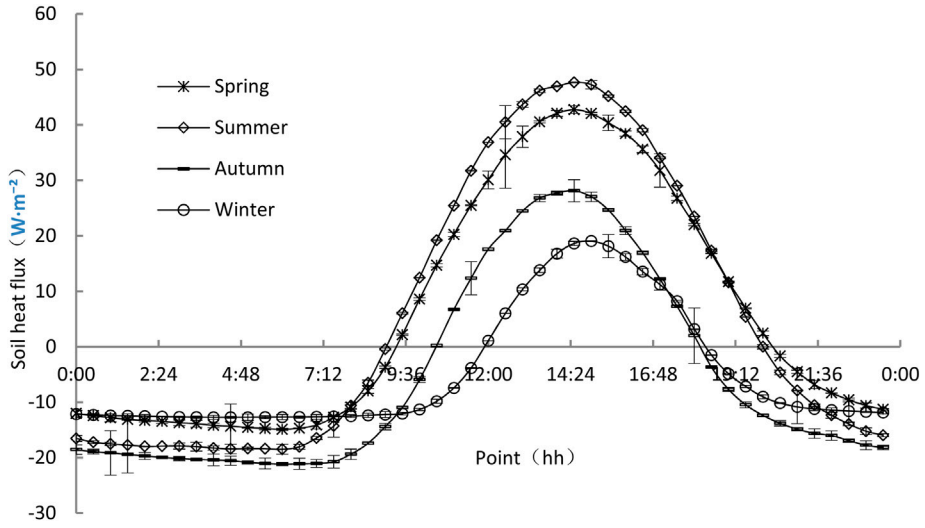


FIGURE 2
Daily variation patterns of soil heat flux in different seasons.

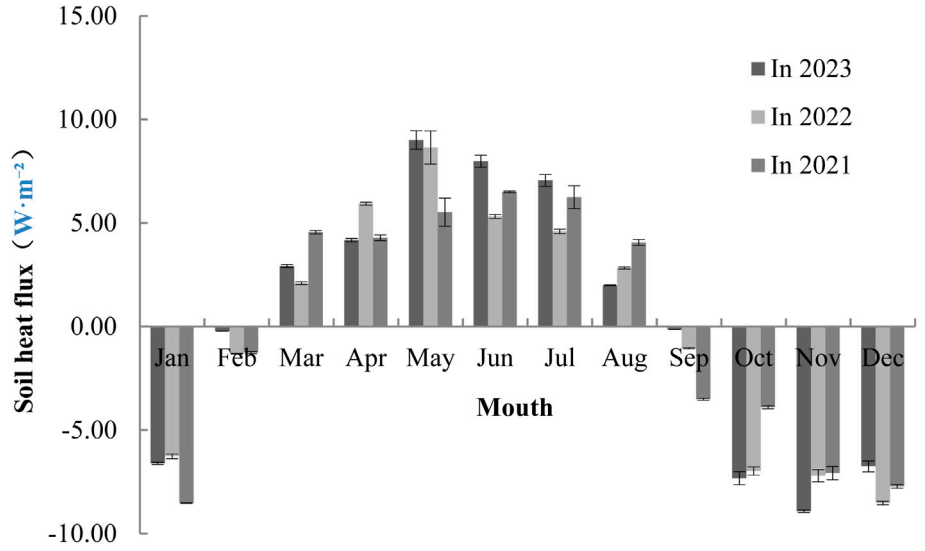


FIGURE 3
Variation patterns of monthly average soil heat flux (W·m^{-2}) in different years (2021–2023). Figure caption: Positive values indicate that the soil acts as a 'heat sink' (absorbing heat from the atmosphere),and negative values indicate that the soil acts as a 'heat source' (releasing heat to the atmosphere).

3 Results and analysis

3.1 Patterns of changes in soil heat flux

3.1.1 Daily patterns of soil heat fluxes in different seasons

Soil heat flux is negative when the deeper soil layers release heat to the soil surface or the atmosphere, and positive when heat is transferred from the soil surface or the atmosphere to the deeper soil layers. The half-hourly continuous data of soil heat flux were averaged for each moment of the month to generate a graph showing the daily progression of the monthly average (Figure 1). Similarly, the data were averaged for each moment of the season to produce a graph illustrating the daily progression across different seasons (Figure 2).

As shown in Figures 1, 2, the monthly average daily change process exhibits a clear "S" shape, with the daily change curve for each month showing distinct trends. A notable peak is also observed, which occurs consistently around 14:30 throughout the year. The size of the peak substantially varies across months, with the order being summer > spring > fall > winter. This peak indicates the maximum heat transfer from the soil surface or the atmosphere to

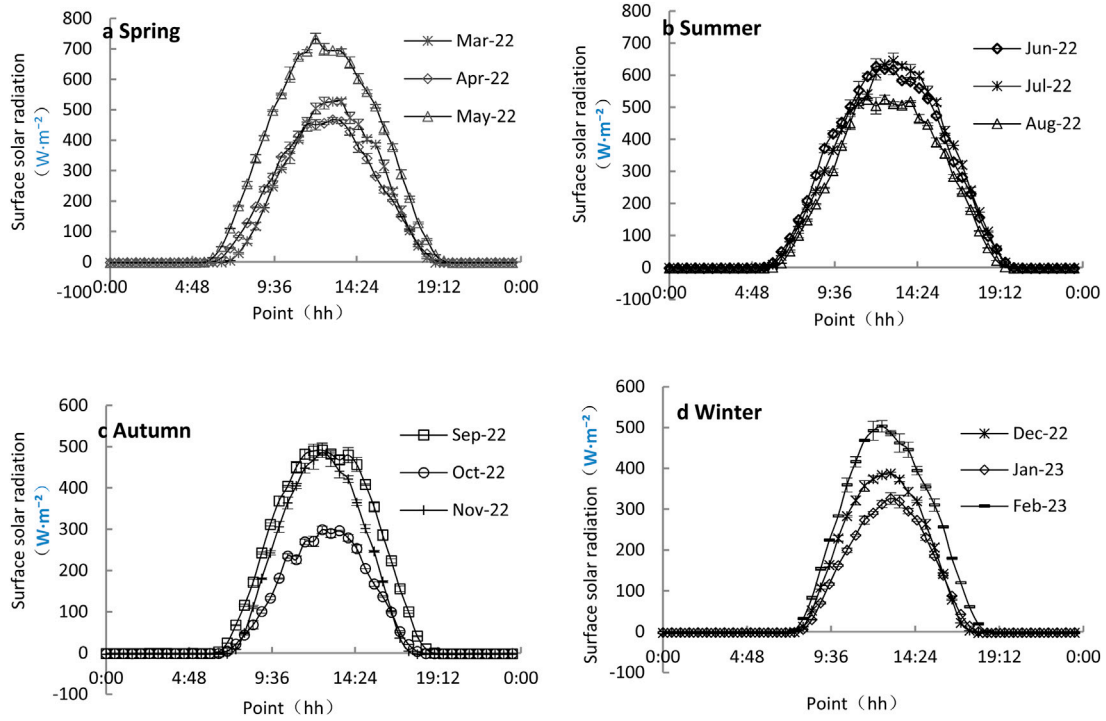


FIGURE 4
Daily variation patterns of surface solar radiation. **(a)** Spring, **(b)** Summer, **(c)** Autumn, and **(d)** Winter. Figure caption: Error bars represent standard deviation (n=3 years for monthly data, n=12 months for seasonal data).

the deeper soil layer. In winter, the peak value indicates the maximum heat transfer from the soil surface or atmosphere to the deep soil layer. The trough and peak values of soil heat flux in the early morning followed different trends, with the order being winter > spring > summer > fall. As the sun rose and set, the time at which the heat flux changed from negative to positive was gradually delayed, while the time for the change from positive to negative in the afternoon was gradually advanced. During the night, the change patterns for summer, fall, and winter were similar, with the values remaining relatively consistent across the seasons. The trough value indicates the maximum heat release from the deep soil layer to the soil surface or to the atmosphere. Although winter nighttime temperatures are the lowest, the heat release is not maximized because the soil temperature in winter is the lowest throughout the year, and the surface soil temperature (or atmospheric temperature) are also at their lowest. Therefore, the temperature difference is smaller, leading to less heat flux exchange during the night. The 'S'-shaped diurnal variation in soil heat flux is primarily driven by solar radiation, which enhances soil surface temperature gradients and promotes downward heat conduction. Soil moisture and heat capacity further modulate peak flux values by altering thermal conductivity (Idso et al., 1975).

3.1.2 Monthly patterns of soil heat fluxes in different years

The pattern of change in the mean soil heat flux for each month of the three different years, namely, 2021, 2022, and 2023, is shown in Figure 3. Notably, the average soil heat flux is positive from March to August, with the soil acting as a "heat sink," transferring heat from the atmosphere to the soil. In contrast, from September to February, the average soil heat flux is negative, indicating that the soil acts as a heat source, transferring heat from the soil to the atmosphere. Monthly soil heat flux variations are driven not only by solar radiation but also significantly modulated by rainfall and soil moisture. The maximum heat flux in 2023 and 2022 occurs in May instead of July and August when temperatures are highest. This anomaly may be related to local climatic characteristics. Specifically, the months of July and August experience higher rainfall and a greater number of rainy days. In May 2023, 65.2 mm of rainfall fell over 7 days, while June saw 87.2 mm of rainfall over 8 days, and July had 98.2 mm of rainfall across 16 days. Increased rainfall raises the water content of the soil, leading to greater heat storage within the soil and reducing the heat release to the atmosphere. For instance, in August 2023, 166 mm of rainfall fell across 16 days, followed by 10 days of rainfall. This higher moisture content in the soil limits the release of heat, supporting the conclusion of Sun Cheng that "soil moisture content and soil heat flux are negatively correlated (Sun et al., 2013)", and is consistent with the statistically significant ($p < 0.001$) negative correlations between soil moisture content/rainfall and soil heat flux presented in Section 2.3 of this study. The negative minimum of soil heat flux in winter occurs during unstable months with considerable uncertainty, which is positively correlated with the daytime temperature differences across different winter months and years. In the northern Qinling foothills, intense summer solar

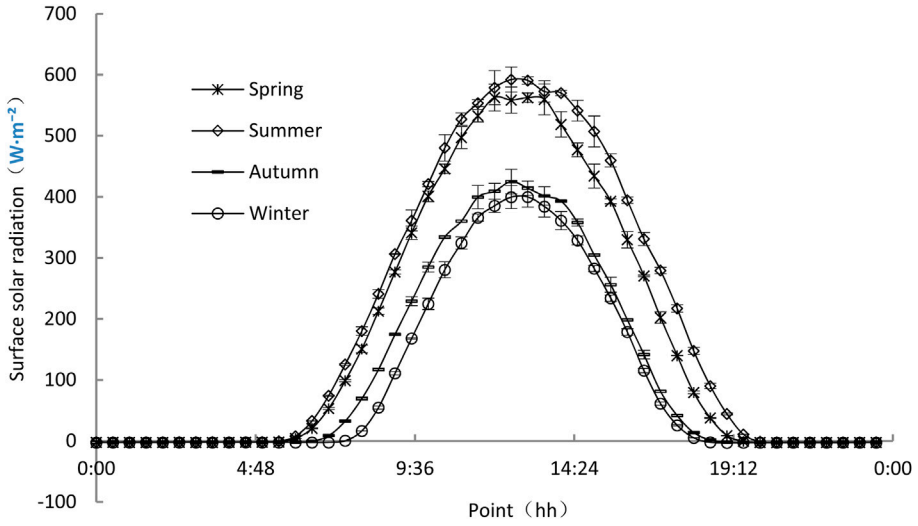


FIGURE 5
Daily variation patterns of surface solar radiation in different seasons.

TABLE 1 Rainfall and rainy days in selected months of 2023 (source: SMR-CR weather station).

	Mouth	Precipitation/mm	Rainfall days/d
1	May 2023	65.2	7
2	June 2023	87.2	8
3	July 2023	98.2	16
4	August 2023	166	10
5	October 2023	116.7	16
6	November 2023	2.9	3
7	December 2023	8.5	4

radiation causes significant surface temperature elevation, creating a strong downward temperature gradient (surface temperature > deep soil temperature) that drives heat flux transfer to deeper soil layers (Wang et al., 2005). During winter, when radiation weakens, surface cooling forms a reverse gradient, leading to upward heat flux release. This dynamic process dominates the seasonal characteristics of regional energy balance by regulating the allocation ratio between surface sensible heat (H) and latent heat (LE).

3.2 Patterns of change in surface solar radiation

3.2.1 Daily patterns of average solar radiation in different seasons

Surface solar radiation reflects sunrise time and light intensity, with evident seasonal differences. As shown in Figures 4, 5, the sunshine duration and light intensity are consistent with summer > spring > autumn > winter, and the difference in sunshine duration between summer (6:00–20:00) and winter (7:30–18:30) is 3 h. The daily variation of surface solar radiation shows the trend of "low in the morning and evening, high at noon" which is mainly due to the smaller solar altitude angle in the morning and evening and the less solar radiation reaches the opposite side. Therefore, the ground absorbs minimal solar radiation at noon. This finding is mainly due to the smaller solar altitude angle in the morning and evening. The solar radiation reaching the opposite side is minimal, and the solar radiation absorbed by the ground is small. Conversely, the opposite is true at noon. The maximum value of surface solar radiation occurs in May, and the minimum value occurs in October, which is not exactly positively correlated with the height of the monthly average temperature. Analysis results of the rainfall in these months (Table 1) reveal that rainfall or cloudy weather has a substantial influence on the solar radiation reaching the ground. This finding is due to the fact that with the increase in the amount of clouds in the sky on cloudy days, the amount of solar radiation received by the ground surface decreases, which is similar to that described in the work of Zhang Mingli in the paper "Rainfall impacts on solar radiation in Qinghai-Tibet". This trend is consistent with the conclusion of Zhang Mingli in the study "Effect of rainfall on surface solar radiation in the permafrost region of the Tibetan Plateau" (Zhang et al., 2021).

3.2.2 Monthly patterns of surface solar radiation in different years

Figure 6 illustrates the monthly changes in mean surface solar radiation over the 3 years. Clear seasonal differences are observed, with spring and summer exhibiting higher radiation levels than autumn and winter. This finding can be attributed to the higher solar altitude angles during spring and summer, compared to the lower angles in autumn and winter. The lower the sun's altitude angle, the longer the distance light travels through the atmosphere, leading to greater energy attenuation. Additionally, during spring and summer, the

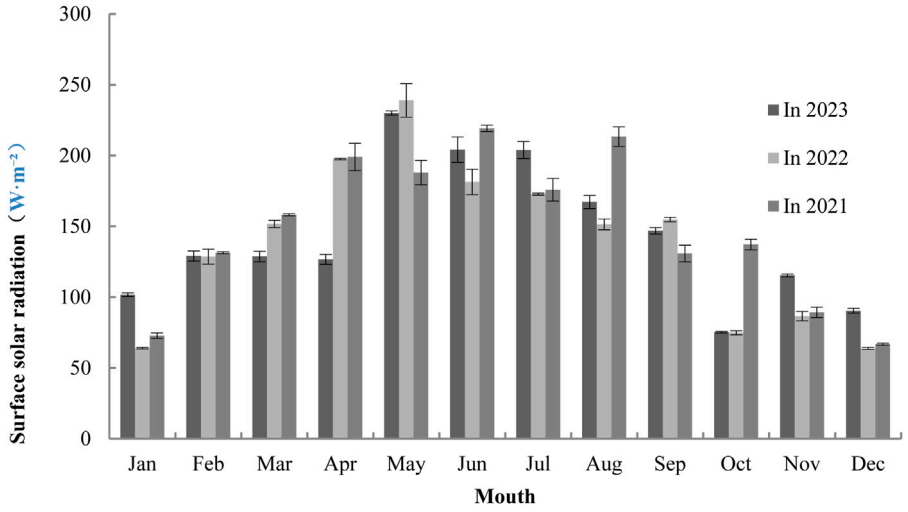


FIGURE 6
Variation pattern of monthly mean surface solar radiation (W·m^{-2}) in different years (2021–2023).

Northern Hemisphere tilts toward the sun, which enhances solar radiation due to the favorable tilt of the Earth's axis. However, the mean value of surface solar radiation only partially aligns with changes in the solar altitude angle and the Earth's axis. This discrepancy is due to the unique climatic conditions in the northern foothills of the Qinling Mountains, where the test site experiences notable rainfall, accounting for more than 50% of the annual precipitation from June to August. The rainy weather and cloud shading reduce the amount of solar radiation reaching the ground.

3.3 Multivariate interaction analysis between environmental factors and soil heat flux

Using annual daily data from 2023, we performed Pearson correlation analysis with Bonferroni correction ($p < 0.001$) to control for multiple testing errors. The Correlation Plot plugin in Origin 2024 was used to visualize pairwise relationships, with VIF values confirming no significant collinearity (all VIF<1.8). We conducted multivariate interaction analysis between Soil heat flux (soil-G-W) and eight environmental factors: ambient temperature (Ta), 20-cm soil temperature (Soil-T-20 cm), 20-cm volumetric soil moisture content (Soil-VWC-20 cm), wind speed (WS), atmospheric pressure (Pa), surface solar radiation (Solar-R), rainfall (Rain), and relative humidity (RH).

The Correlation Plot plugin in Origin 2024 was employed to analyze daily averages of these parameters. Notably, lag effects exist between some environmental variables and G: for example, rainfall events may suppress G for 1–2 days due to increased soil moisture reducing thermal conductivity—a pattern consistent with transient changes in soil thermal properties (Xu et al., 2013). As shown in Figure 7, surface solar radiation dominated soil heat flux variation with an statistically significant positive correlation ($r = 0.83$, $p < 0.001$), and environmental temperature showed a strong positive correlation with soil heat flux ($r = 0.72$, $p < 0.001$). Soil temperature at 20 cm, soil moisture at 20 cm, and wind speed showed significant positive correlations ($r = 0.57$, 0.24, and 0.27 respectively), while atmospheric pressure, rainfall, and humidity demonstrated significant negative correlations ($r = -0.70$, -0.27, and -0.18 respectively).

3.4 Correlation analysis between surface solar radiation and soil heat flux on different time scales

Soil heat flux and solar radiation were averaged for each day from January to June 2023, and a binary regression analysis was performed on the two parameters. The daily soil heat flux and solar radiation showed a highly significant correlation with a significance level of 0.001, with a coupling relationship of $G_{soil} = 0.083R_{Solar}$-10.56 and a fitting coefficient of $R^2 = 0.8502$, "R_{solar}" is defined as surface solar radiation. as shown in Figure 8.

Monthly mean values of soil heat flux and solar radiation were collected from January to June 2023. Regression analysis of their mean values showed highly significant correlation with a significance level of 0.001, as shown in Figure 9, with a coupling relationship of $G_{soil} = 0.0863R_{Solar}$-11.152 and a fitting coefficient of $R^2 = 0.9249$.

The correlation between soil heat flux and surface solar radiation was highly significant on daily and monthly scales. This finding is attributed to the fact that solar radiation is the main source of soil heat flux. During the fall and winter seasons or at night, the soil acts as a heat source, transferring energy from the soil to the atmosphere. In contrast, during the spring and summer seasons or during the daytime, when sunlight is more abundant, the soil functions as a heat sink, absorbing solar radiation and soring heat. However, considering the correlation coefficient, the relationship is more closely observed on the monthly scale, which is also consistent with the findings of Park et al. (2017), Sun et al. (2013) and Hu et al. (2014) who demonstrated the correlation between soil heat flux and net radiation. The clear linear relationship between soil heat flux and

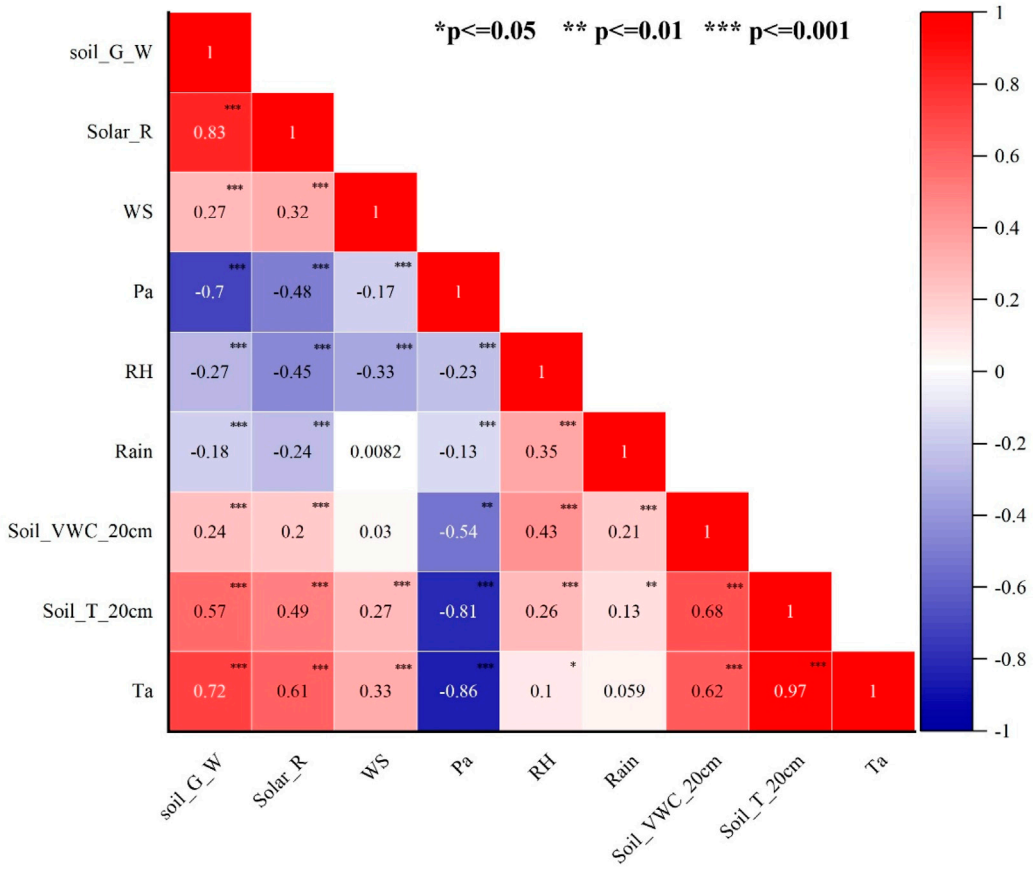


FIGURE 7
Heatmap of multivariate interaction analysis between environmental factors and soil heat flux.

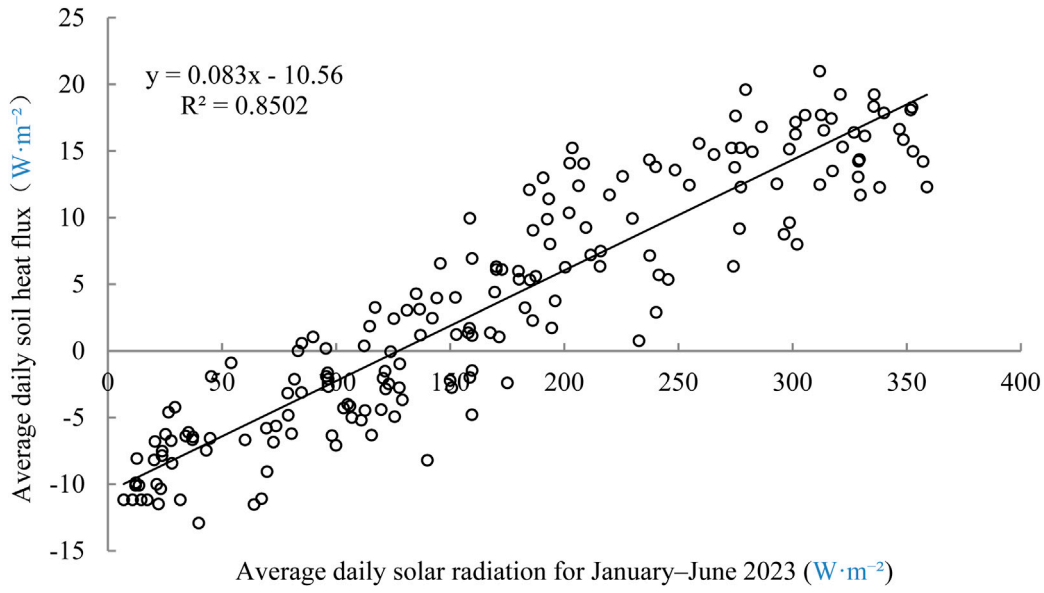


FIGURE 8
Analysis of the correlation between soil heat flux and surface solar radiation on a daily time scale.

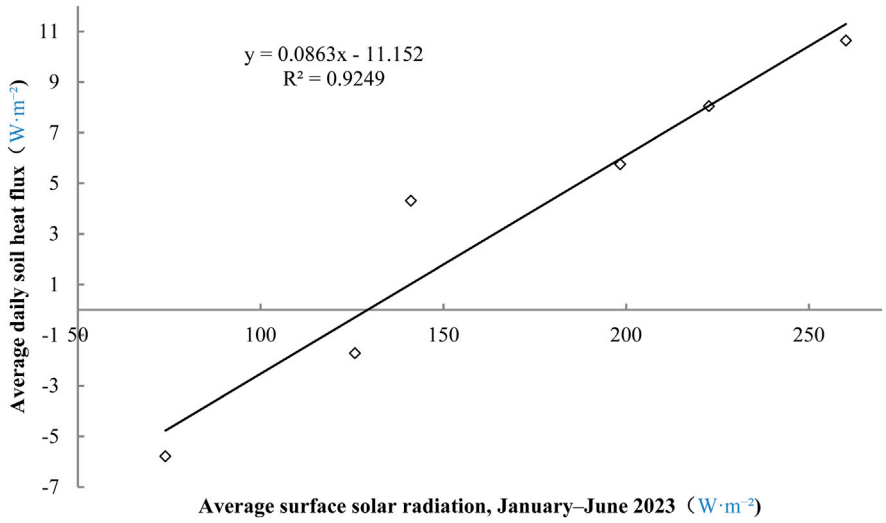


FIGURE 9
Correlation analysis of soil heat flux and surface solar radiation on a monthly time scale.

surface solar radiation in this study may also be related to the minimal influence of cover factors, such as plant leaf area index and canopy height, around the meteorological stations involved in this study. The stronger monthly-scale correlation ($R^2 = 0.92$) compared to the daily scale ($R^2 = 0.85$) may arise from two factors: (1) Thermal lag effects, where soil heat flux responds to radiation changes with a delay of 1–3 h (Li et al., 2022b); (2) Daily-scale measurement errors from turbulent flux fluctuations and short-term rainfall-induced soil moisture changes (Xu et al., 2013), which are mitigated by monthly averaging.

4 Discussion and conclusion

4.1 Analysis of variation patterns in soil heat flux and surface solar radiation

The results show that soil heat flux (G) exhibits pronounced diurnal variations and distinct seasonal characteristics. The diurnal amplitude of G is smaller in winter and largest in summer. During the daytime, as solar radiation increases after sunrise, heat flux transfers from the atmosphere and soil surface to deeper soil layers, leading to a rise in soil temperature. After sunset, as solar radiation decreases, heat flux shifts direction, transferring heat from deeper soil layers to the surface and atmosphere, accompanied by a decline in soil temperature. This demonstrates that soil temperature dynamics are governed by soil heat flux.

In the northern foothills of the Qinling Mountains, seasonal analysis reveals that G is positive (soil acting as a "heat sink," with heat transferred from the atmosphere to the soil) during spring and summer, and negative (soil acting as a "heat source," with heat released from the soil to the atmosphere) during autumn and winter. The timing of sign transitions varies across seasons. The monthly mean G remains positive from March to August (7.296×10^3 MJ m^{-2}), while it becomes negative from September to February, peaking at −22.58 MJ m^{-2} in December. These seasonal patterns are primarily driven by variations in solar radiation intensity.

On an annual scale, the soil acts as a net heat sink (7.296×10^3 MJ m^{-2}), while winter exhibits a net heat source ($-4.197 \times 10^{4.1}$ MJ m^{-2}). Annual surface solar radiation totals 1.721×10^6 MJ m^{-2}, with soil heat flux accounting for 2.44% of this total. Although this proportion is small, monthly-scale analysis reveals that G can contribute up to 9.41% of surface solar radiation (e.g., December). This highlights that soil heat flux cannot be neglected at finer temporal scales and significantly impacts assessments of ecosystem energy closure. These findings align with studies (Yue et al., 2012; Wang H. et al., 2022), which report that ignoring G reduces energy balance closure rates by 5%–8%. Seasonal variations in soil heat flux may influence local vegetation phenology. For example, the emergence of Moso bamboo shoots requires soil temperatures ≥13 °C for 10 consecutive days (Sun et al., 2013). The positive soil heat flux from March to May helps meet this temperature threshold, highlighting the agricultural and ecological guiding significance of studying soil heat flux.

4.2 Correlation analysis between environmental factors and soil heat flux

Multivariate interaction analysis of environmental factors and surface solar radiation indicates that solar radiation dominates soil heat flux dynamics. As the core driver of surface energy balance, solar radiation directly regulates net surface solar radiation (R_n) and indirectly influences soil thermodynamic processes, exerting a decisive control on Guo et al. (2015). Recent studies further confirm the direct regulatory role of solar radiation on soil heat flux (Zan et al., 2024; Wang Y. et al., 2022). Additionally, environmental factors such as air temperature, soil temperature, wind speed, air pressure, humidity, and soil moisture show significant correlations with G: Temperature modifies soil thermal properties (e.g., thermal conductivity and diffusivity) to

directly influence heat flux (Park et al., 2017). Vertical soil temperature gradients are the primary driver of heat conduction, with larger temperature differences between surface and deeper layers amplifying G. During daytime surface warming, heat transfers downward (positive G); nighttime cooling reverses this process (negative G) (Miao et al., 2012; Liu et al., 2024). Global observations indicate that a 1 K soil temperature anomaly increases energy closure bias by over 3 W m^{-2}, significantly elevating sensible heat flux (Fu et al., 2024). Soil moisture regulates G by altering soil heat capacity and thermal conductivity (Idso et al., 1975). Increased moisture replaces air in soil pores, enhancing thermal conductivity and heat transfer efficiency, thereby substantially impacting G calculations (Wu et al., 2020; Chang et al., 2021). Wind speed indirectly affects G through turbulent exchange. Strong winds accelerate surface evaporative cooling, reducing surface soil temperature gradients and suppressing heat transfer to deeper layers (Wu et al., 2020; Liu et al., 2024). Air pressure influences G via changes in air density and gas movement in soil pores. Under low-pressure conditions, reduced air density lowers thermal conductivity, potentially inhibiting heat transfer (Guo and Sun, 2002).

The combined effects of these environmental factors exhibit synergistic coupling. Future research must integrate multi-scale observations and dynamic models to improve the prediction accuracy of surface energy closure rates.

4.3 Correlation analysis between surface solar radiation and soil heat flux across temporal scales

Bivariate regression confirms a linear relationship between soil heat flux and surface solar radiation at both daily and monthly scales, with correlations reaching extreme significance ($p < 0.01$). The monthly-scale correlation is stronger ($r = 0.9249$), as daily-scale relationships are disrupted by transient meteorological disturbances (e.g., abrupt cloud cover, precipitation, and wind gusts) that cause asynchronous fluctuations between surface solar radiation and G. For example, precipitation alters soil moisture, thereby modifying thermal conductivity and heat transfer efficiency. While cloud cover may simultaneously reduce surface solar radiation, phase differences between radiation and G responses can span several hours (Xu et al., 2013). Additionally, diurnal variations in G exhibit significant thermal lag effects (Li et al., 2022b; Xu et al., 2013), and low energy balance closure rates (70%–90%) due to turbulent flux measurement errors and soil heat storage calculation biases further obscure daily-scale linear relationships (Xu et al., 2013; Yang D. et al., 2024).

In contrast, monthly averaging mitigates short-term noise, weakens thermal hysteresis, improves energy closure, and enhances seasonal synchrony, thereby strengthening the linear correlation between G and surface solar radiation (Yang Y. et al., 2024). This finding holds critical implications for parameterizing land surface models under mountainous terrain, such as refining the soil moisture-thermal conductivity modules in the Noah-MP model to account for the 1–2 days lag effect between rainfall and soil heat flux observed in this study. For the Community Land Model (CLM), our results support adjusting the energy closure algorithm to incorporate the stronger monthly-scale correlation ($R^2 = 0.92$) between surface solar radiation and soil heat flux, reducing biases in mountainous energy balance simulations. Additionally, in the WRF-LSM model, the distinct diurnal 'S'-shaped pattern of soil heat flux (driven by solar radiation) can inform improvements to the diurnal cycle parameterization of surface energy exchange in the Qinling foothills, enhancing the model's ability to capture local microclimate dynamics. Monthly-scale data are better suited for long-term regional energy balance analysis, and future studies should quantify threshold effects of temporal scale transitions across ecosystems to optimize the spatiotemporal resolution of global energy balance simulations.

4.4 Global implications

The findings from this study highlight the unique energy exchange mechanisms in mid-latitude montane ecosystems like the northern Qinling foothills, contrasting with other globally studied regions such as the Tibetan Plateau and desert areas. For instance, soil heat flux in alpine grasslands of the Tibetan Plateau is predominantly driven by solar radiation and soil temperature gradients (Zhang et al., 2020; Li et al., 2022), with limited influence from soil moisture due to the arid climate. In desert ecosystems (e.g., Gurbantunggut Desert), surface solar radiation dominates heat flux dynamics, while soil moisture plays a negligible role in energy balance (Cao et al., 2021; Chang et al., 2021). By contrast, the Qinling foothills exhibit a more complex interplay of environmental factors: soil moisture ($r = 0.24$, $p < 0.001$) and wind speed ($r = 0.27$) significantly modulate heat flux, reflecting the region's higher precipitation (581.6 mm/year) and loessial soil properties that enhance thermal conductivity during wet seasons (Fu et al., 2017).

This mid-latitude montane sensitivity to both radiative and hydrological processes underscores its role as a critical "energy buffer" in climate regulation. Unlike low-latitude tropical forests or high-latitude tundra, the Qinling system experiences distinct seasonal transitions in heat source/sink functions (positive flux from March to August, negative from September to February), which are tightly linked to monsoon-driven precipitation patterns. Such dynamics have broader implications for global land surface model parameterization, particularly in regions with similar climatic regimes (e.g., the U.S. Appalachian Mountains, European Alps). Incorporating soil moisture–radiation feedbacks observed here could improve the accuracy of energy balance simulations in mid-latitude mountainous zones, which are often underrepresented in global climate models (Yang Y. et al., 2024; Zan et al., 2024).

Chaturvedi et al. highlighted hydro-climatic dynamics in river systems, which is conceptually similar to the coupled soil-atmosphere-hydrology feedbacks in the Qinling region (Chaturvedi et al., 2024). Zhang et al. reviewed environmental biogeochemical cycles under external stressors, providing insights into the link between soil heat flux and biogeochemical processes in this study area (Zhang et al., 2024). Chaturvedi et al. discussed soil-ecology interactions, emphasizing that soil fauna and fungi may modulate heat transfer, which is a potential direction for future research in the Qinling foothills (Chaturvedi et al., 2025). These findings theoretically enhance our understanding of soil-vegetation-atmosphere energy exchange in mid-latitude montane ecosystems and practically support agricultural irrigation scheduling (e.g., optimizing water use based on soil heat flux dynamics), ecological restoration strategies and regional climate

model parameterization. In the specific context of the northern foothills of the Qinling Mountains (our study area), such practical implications can be further illustrated through local scenarios: For one, soil heat flux (G) changes affect the phenology of local typical vegetation Quercus aliena var. acuteserrata—a rise in spring G advances its leaf emergence by 2–3 days, while a drop in autumn G delays leaf senescence by 1–2 days, which provides a clear basis for optimizing local ecological restoration planning. For another, regarding winter wheat (the main food crop in this region), when the daily average G during the jointing stage exceeds 8 W m^{-2}, the soil maintains sufficient moisture for crop growth; farmers can thus adjust irrigation frequency from once every 7 days to once every 10 days, reducing seasonal water use by about 15% without impacting yield.

This study has two main limitations: (1) The single-site bare soil design may not fully represent vegetated areas; future studies should include vegetated plots (e.g., mixed deciduous broadleaf forests) to explore the impact of vegetation coverage on heat flux dynamics and enhance the generalizability of findings; (2) The 3-year dataset limits long-term trend analysis, necessitating multi-decadal observations in the future. Future research should integrate remote sensing data (e.g., MODIS land surface temperature) and WRF-LSM models to upscale the research scale and investigate soil heat flux responses to extreme climate events (such as prolonged droughts or heavy rainfall).

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

ZP: Conceptualization, Writing – original draft, Data curation, Validation. DH: Writing – review and editing, Supervision, Conceptualization, Funding acquisition, Project administration. JuL: Formal Analysis, Writing – original draft, Conceptualization, Software. JiL: Writing – review and editing, Methodology, Software.

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Conflict of interest

Authors ZP, DH, JuL, and JiL were employed by Shaanxi Provincial Land Engineering Construction Group Co., Ltd. Authors ZP, DH, JuL, and JiL were employed by Shaanxi Agricultural Development Group Co., Ltd. Author DH is affiliated with the Innovation Center for Land Engineering and Human Settlements, a joint initiative between Xi'an Jiaotong University and Shaanxi Land Engineering Construction Group Co., Ltd.

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Assessing the scientific basis and regional applicability of a Chinese agrometeorological proverb in a warming climate

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Chinese Agrometeorological Proverbs represent a valuable repository of traditional knowledge supporting agricultural practices; however, their scientific validity and regional applicability under climate change remain insufficiently examined. This study evaluates the proverb "The heat of Dog Days on double Beginning of Spring of the Lunar Years" using daily meteorological data from 699 stations across China (1966–2019). We compared temperature trends between Double-Beginning of Spring Lunar Years (BSLY) and Normal Years (NY) from the Beginning of Spring to Minor Heat to identify periods of "Rapid Warming" (RW), and assessed the intensity of "Dog Days Heat" (DDH) using the Temperature-Humidity Index (THI). The results reveal spatially varying consistency with the RW characteristic: southern China and the middle-lower Yellow River basin showed the strongest agreement, meeting the RW criterion within both 31 and 46 days after the Beginning of Spring. During the Dog Days period, BSLY exhibited significantly higher heat intensity in southern regions, with spatial variations influenced by topography and local climate conditions. This research confirms the scientific basis of the proverb and demonstrates that its applicability extends beyond its region of origin. The findings provide practical insights for integrating traditional knowledge into climate-resilient agricultural planning, supporting adaptive strategies under changing climatic conditions.

KEYWORDS

agrometeorological Proverbs, climate change, least-square fitting, temperature-humidity index, regional agroclimate

1 Introduction

Chinese Agrometeorological Proverbs represent a traditional knowledge system developed within the framework of the Twenty-Four Solar Terms, which are themselves based on the lunisolar calendar traditionally used in China. This calendar integrates the cycles of the moon and the sun, and its 24 solar terms were established to reflect annual cyclical climate changes, serving as a unique timeline guiding agricultural activities and daily life. These solar terms provide the fundamental temporal framework for the formation and application of Agrometeorological Proverbs. The proverbs essentially encapsulate empirical observations about the relationships between these solar terms, weather patterns, and phenological phases, forming a condensed body of practical knowledge

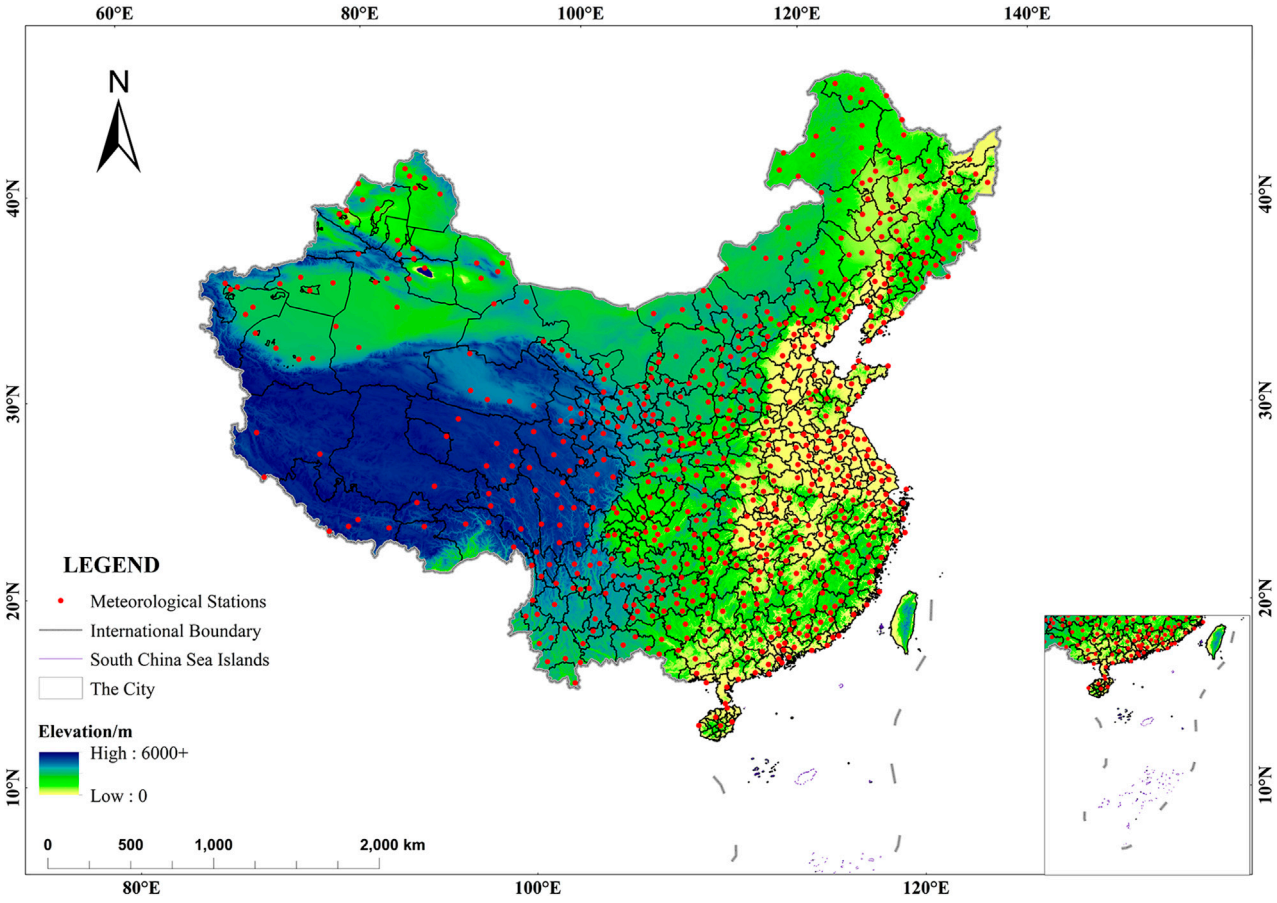


FIGURE 1
Study area and distribution of weather stations (no station data for Taiwan).

for agricultural production. Formed through long-term observation of weather and phenological changes combined with agricultural practices. These proverbs embody the empirical wisdom essential for agricultural production and crop management (Chen, 2016). Their origins can be traced back to oracle bone inscriptions from the Shang Dynasty (c. 1,300–1,046 BC), which already contained records of climate-related proverbs (Mu and Ali, 2023). Later, these sayings were systematically compiled and developed in ancient agricultural texts such as of the Western Han Dynasty (202 BC-8 AD) and "Qi Min Yao Shu" of the Northern Wei Dynasty (386–534 AD) (Jia, 2024). Throughout China's long agricultural history, these proverbs have been refined through repeated practice and ultimately evolved into a knowledge system possessing both cultural and scientific significance. Proverbs from different regions reflect varied climatic characteristics—for instance, "No more snow after Pure Brightness, but often a small amount of snow; no frost after Grain Rain, but there may be some frost" in North China and "No snow after Pure Brightness, no frost after Grain Rain" in the middle and lower reaches of the Yangtze River—and often guide farming activities based on phenological phenomena. However, the scientific validity of these proverbs under modern climate change remains subject to systematic verification. In this context, temperature-related proverbs deserve particular attention. For example, "The heat of Dog Days on double Beginning of Spring of the Lunar Years" suggests that in years with BSLY markers in the lunar calendar, an earlier and more rapid spring warming occurs, which may lead to higher temperatures during the Dog Days. However, the meteorological mechanisms underlying this association have not yet been rigorously validated.

As the foundation of Agrometeorological Proverbs, the twenty-four solar terms were inscribed on the Representative List of the Intangible Cultural Heritage of Humanity by the United Nations Educational, Scientific and Cultural Organization (UNESCO) on 30 November 2016, in accordance with Article 16 of the Convention. The twenty-four solar terms can be traced back to the observations and summaries made by ancient Chinese agricultural societies of natural phenomena. From early astronomical observations to the refinement of astronomy and calendrical systems during the Zhou Dynasty (1046 BC-256BC), terms like Beginning of Spring, Beginning of Summer, Beginning of Autumn, and Beginning of Winter were applied to people's daily life and agricultural production activities, to the Qin and Han dynasties (221 BC-220 AD) formed a more complete Twenty-four solar terms, clearly taking one cycle of the Earth's rotation around the Sun as a cycle, that is, the Sun from the zero degree of the ecliptic longitude, along the ecliptic longitude every 15° run as a solar term (Xu and Wang, 2018). The twenty-four solar terms start from the Beginning of Spring and end with the Major Cold,

TABLE 1 The time periods of the twenty-four solar terms over the years and their selected reference dates.

Solar term	Time periods (Month/day)	Selected date (Month/day)	Solar term	Time periods (Month/day)	Selected date (Month/day)
Beginning of Spring	2/3–2/5	2/4	Rain Water	2/18–2/19	2/19
Awakening of Insects	3/5–3/6	3/6	Spring Equinox	3/20–3/21	3/21
Pure Brightness	4/4–4/5	4/5	Grain Rain	4/20–4/21	4/21
Beginning of Summer	5/5–5/6	5/6	Grain Buds	5/20–5/22	5/21
Grain in Ear	6/5–6/6	6/6	Summer Solstice	6/21–6/22	6/22
Minor Heat	7/7–7/8	7/8	major Heat	7/22–7/23	7/23
Beginning of Autumn	8/7–8/8	8/8	End of Heat	8/23–8/24	8/24
White Dew	9/7–9/8	9/8	Autumnal Equinox	9/22–9/24	9/23
Cold Dew	10/8–10/9	10/9	Frost's Descent	10/23–10/24	10/24
Beginning of Winter	11/7–11/8	11/8	Minor Snow	11/22–11/23	11/23
Major Snow	12/7–12/8	12/8	Winter Solstice	12/21–12/22	12/22
Minor Cold	1/5–1/6	1/6	Major Cold	1/20–1/21	1/21

TABLE 2 Type of year and length of Dog Days.

Year	Type	Dog days start and end date (Month/day)	Year	Type	Dog days start and end date (Month/day)	Year	Type	Dog days start and end date (Month/day)
1966	BSLY	7/20–8/18	1967	NY	7/15–8/23	1968	BSLY	7/19–8/17
1969	NY	7/14–8/22	1970	NY	7/19–8/17	1971	BSLY	7/14–8/22
1972	NY	7/18–8/16	1973	NY	7/13–8/21	1974	BSLY	7/18–8/16
1975	NY	7/13–8/21	1976	BSLY	7/17–8/25	1977	NY	7/12–8/20
1978	NY	7/17–8/25	1979	BSLY	7/12–8/20	1980	NY	7/16–8/24
1981	NY	7/11–8/19	1982	BSLY	7/16–8/24	1983	NY	7/11–8/19
1984	BSLY	7/15–8/23	1985	NY	7/20–8/18	1986	NY	7/15–8/23
1987	BSLY	7/20–8/18	1988	NY	7/14–8/22	1989	NY	7/19–8/17
1990	BSLY	7/14–8/22	1991	NY	7/19–8/17	1992	NY	7/13–8/21
1993	BSLY	7/18–8/16	1994	NY	7/13–8/21	1995	BSLY	7/18–8/16
1996	NY	7/12–8/20	1997	NY	7/17–8/25	1998	BSLY	7/12–8/20
1999	NY	7/17–8/25	2000	NY	7/11–8/19	2001	BSLY	7/16–8/24
2002	NY	7/11–8/19	2003	NY	7/16–8/24	2004	BSLY	7/20–8/18
2005	NY	7/15–8/23	2006	BSLY	7/20–8/18	2007	NY	7/15–8/23
2008	NY	7/19–8/17	2009	BSLY	7/14–8/22	2010	NY	7/19–8/17
2011	NY	7/14–8/22	2012	BSLY	7/18–8/16	2013	NY	7/13–8/21
2014	BSLY	7/18–8/16	2015	NY	7/13–8/21	2016	NY	7/17–8/25
2017	BSLY	7/12–8/20	2018	NY	7/17–8/25	2019	NY	7/12–8/20

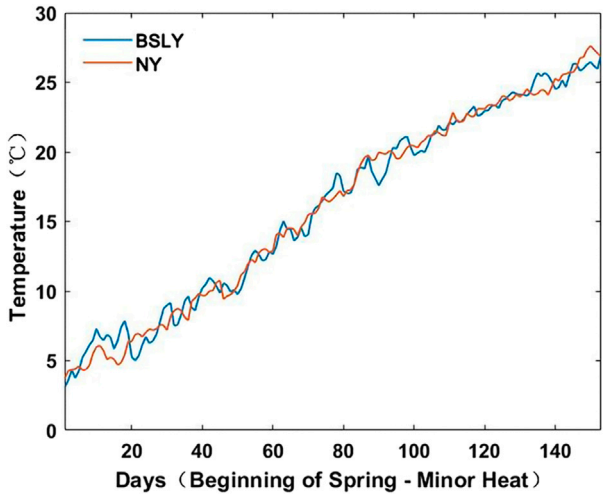


FIGURE 2
Comparison chart of raw temperature data.

TABLE 3 Dog days "Degree of Heat" of compliance criteria.

Difference	Degree of conformity
$D_h + D_l > 0$	"DDH" strong
$D_h + D_l = 0$	"DDH" weak
$D_h + D_l < 0$	Proverbs are not suitable

which reflects the climate changes in different temporal periods of the year in detail, for example, Beginning of Spring, Beginning of Summer, Beginning of Autumn, and Beginning of Winter represent the beginning of the four seasons, and Awakening of Insects, Pure Brightness, Grain Buds, and Grain in Ear not only represent climate changes, which also reflects the phenological phenomenon of crops. In addition to the main twenty-four solar terms, there exist other important secondary solar terms, like Dog Days, which are used to define in detail the hottest time of the year (Xu, 2024). Traditional meteorological culture, including the twenty-four solar terms and agrometeorological proverbs, not only had far-reaching influences

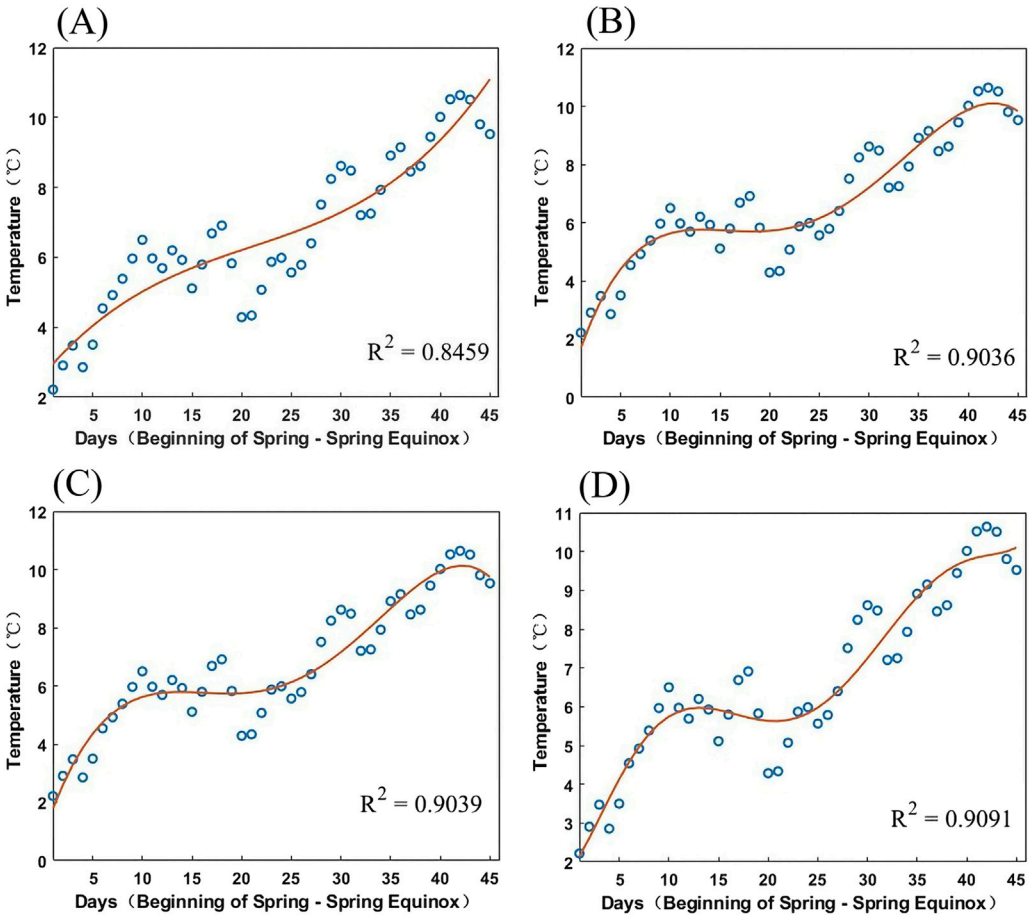


FIGURE 3
Comparison of different degree fitting of polynomial (Note: degree of polynomial, **(A)** 3, **(B)** 4, **(C)** 5, **(D)** 6).

TABLE 4 Warming result division.

Warming temporal period	Conformity division	Differences
Beginning of Spring to Awakening of Insects, Beginning of Spring to Spring Equinox	"RW" strong	High warming amplitude; Long warming time
Beginning of Spring to Awakening of Insects	"RW" moderate	High warming amplitude
Beginning of Spring to Spring Equinox	"RW" weak	Long warming time
No significant warming period	Not conforming	

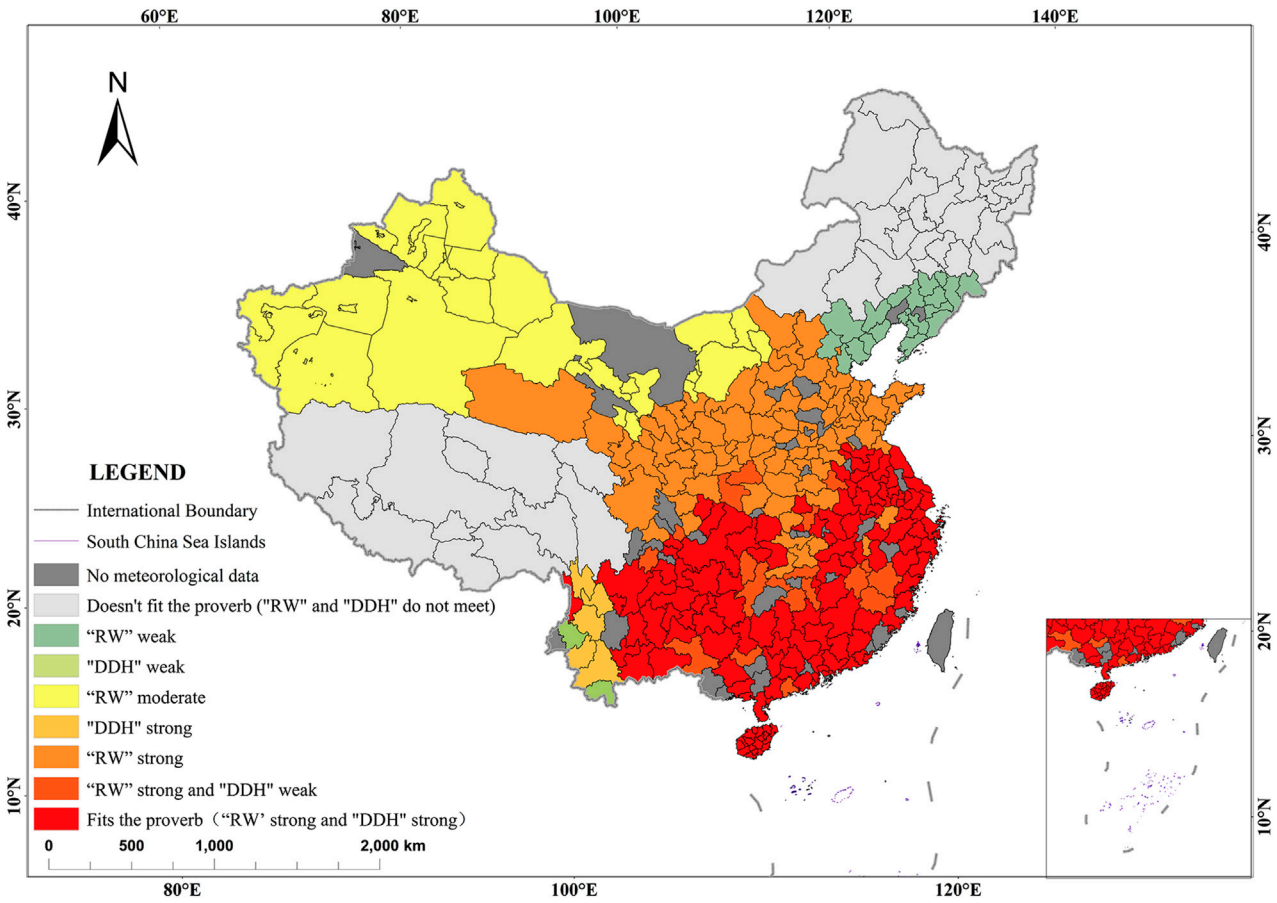


FIGURE 4
Regional conformity types for "The heat of Dog Days on double Beginning of Spring of the Lunar Years" proverb.

in the history of Chinese civilization, but also occupies an important position in the history of world civilization and is receiving more attention from researchers.

In recent years, increasing climate variability has drawn widespread attention to agricultural meteorological proverbs due to their potential in modern adaptation strategies. The inclusion of the "Twenty-Four Solar Terms" in the UNESCO Intangible Cultural Heritage List in 2016 has further stimulated research in this field. Frequent extreme climate events—such as the record-breaking heatwaves across multiple countries and spatially compound heat events in 2023 (Zhang W. et al., 2024) —pose severe threats to global food security. These challenges have prompted the scientific community to re-evaluate the predictive and practical value of traditional agricultural weather proverbs. In this domain, international research methodologies have gradually shifted from early descriptive analysis toward more scientific and empirical approaches. Studies globally can be broadly categorized into two main themes: (i) examining the correlation between proverbs and climatic factors, and (ii) assessing the accuracy of proverbs under climate change. For instance, Kanno et al. (2013) illustrated the relationship between proverbs, local climate and global climate elements like ENSO (El Niño and Southern Oscillation) by comparing proverbs from the Sinazongwe District of Zambia's Southern Province with modern meteorological records; meanwhile, Garteizgogeascoa et al. (2020) studied local perceptions of climate change through proverbs, taking the Sierra Nevada region of Spain as an example, and the results showed both consistency and inconsistency between people's perceptions of the proverbs' accuracy and the information available from science-based assessments of the impacts of climate change in the region. Notably,

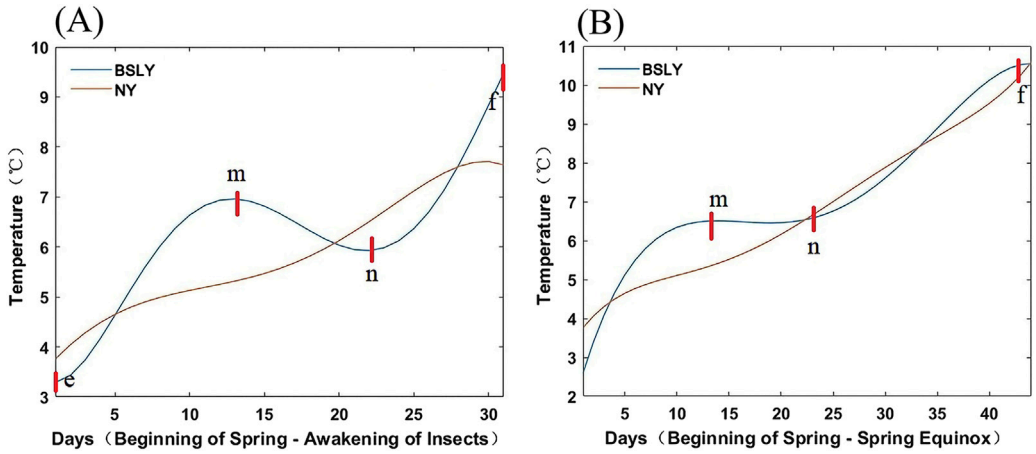


FIGURE 5
Temperature trend map of regions with strong conformity to the warming pattern (Note: Taking Huzhou, Zhejiang Province, as an example). (e, m, n, f) denote specific time points as defined in the text. **(A)** Beginning of Spring - Awakening of Insects. **(B)** Beginning of Spring - Spring Equinox.

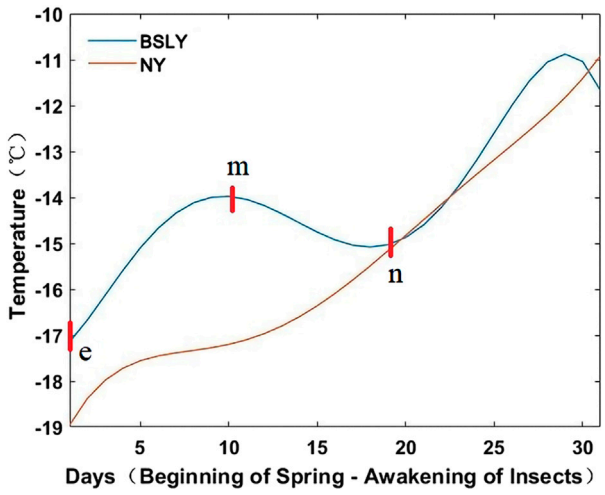


FIGURE 6
Temperature trend map of regions with moderate conformity to the warming pattern (Note: Taking Altai, Xinjiang Uyghur Autonomous Region as an example).

Matczak et al. (2020) used meteorological data to statistically analyze temperature-related proverbs in Poland, and in their studies were found that proverbs' accuracy inversely correlates with chronology (decreased with time), and their values increase in the direction of the east and north of the station site. In contrast, domestic research specifically focused on temperature-predicting proverbs remains relatively limited, with existing work predominantly centered on the solar terms themselves. Qian et al. (2012) indicated that there is a general tendency to advance the four climatic solar terms reflecting phenological phenomena within China, and many agricultural proverbs and experiences related to solar terms may become no longer appropriate; Ji et al. (2015) found a significant increase in (mean, maximum and minimum) temperatures in the spring-type seasons in their study of the twenty-four solar terms in the middle and lower reaches of the Yellow River, and in the winter-type seasons, only the minimum temperatures increased significantly. Despite these findings, there remains a notable research gap in the systematic validation of temperature-predicting proverbs—particularly those based on astronomical or phenological indicators for predicting thermal conditions. As a result, the scientific validity and regional applicability of these traditional proverbs under modern climate conditions remain open to critical questioning. There is an urgent need to move beyond macro-level comparative research paradigms and conduct targeted verification of the climate predictive functions embedded in the proverbs—such as the relationship between "Double Beginning of Spring" and the intensity of summer heat—to provide a scientific basis for sustainable agricultural adaptation measures.

This study selects the widely circulated Agricultural Meteorological Proverb "The heat of Dog Days on double Beginning of Spring of the Lunar Years", which has a deep historical background in the farming civilization of the Jiangsu, Zhejiang, and Shanghai regions. The proverb originates from the empirical observation of the occurrence of double "Beginning of Spring" periods in a lunar year, reflecting the idea that warm air arrives early, the temperature increases rapidly, and heat accumulates quickly, leading to abnormally high temperatures during the Dog Days. In order to explore the Scientificity of the proverb and clarify its regional applicability, thus providing reliable scientific guidance for more accurate climate change predictions in agricultural production, this study focuses on the characteristics of "Rapid Warming" (RW) and "Dog Days Heat" (DDH) in double Beginning of Spring of the Lunar Years (BSLY). The research utilizes comprehensive data collected from 699 meteorological stations between 1966 and 2019 to conduct an in-depth analysis.

2 Area and data

2.1 Study area

China, as the third-largest country in the world by land area, is located in the eastern part of Asia, on the western edge of the Pacific

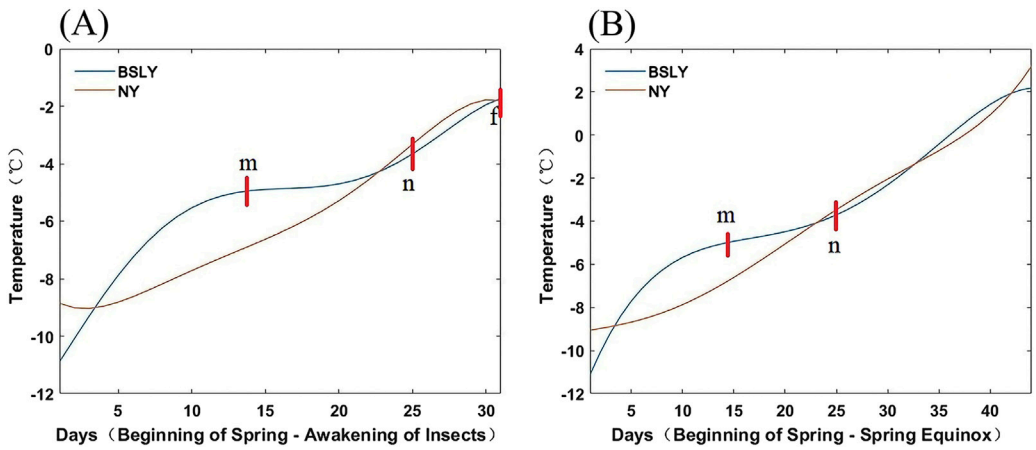


FIGURE 7
Temperature trend map of regions with weak conformity to the warming pattern (Case Study: Shenyang, Liaoning). (m, n, f) denote specific time points as defined in the text. **(A)** Beginning of Spring - Awakening of Insects. **(B)** Beginning of Spring - Spring Equinox.

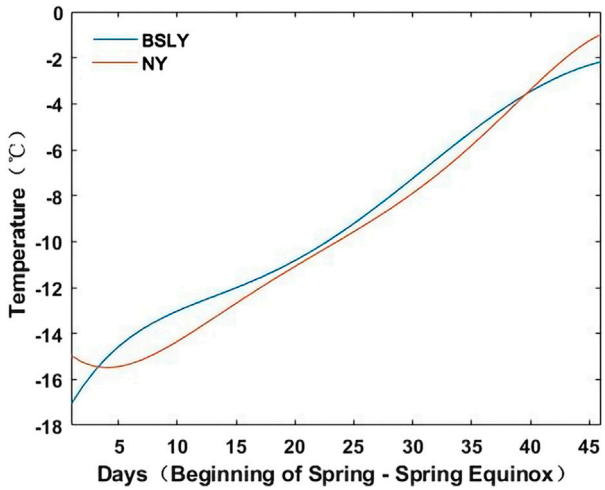


FIGURE 8
Temperature trend map of regions not conforming to the warming pattern (Case Study: Harbin, Heilongjiang).

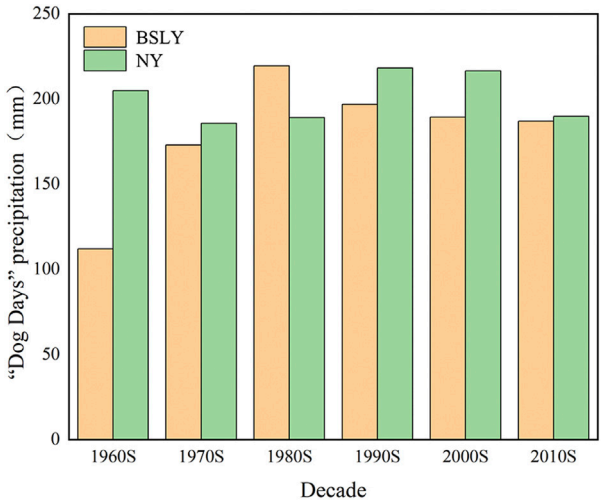


FIGURE 9
A comparison of rainfall during Dog Days across different decades in southern regions. (Note: The decade includes 10 years: Example 1970–1979, and so on. includes 1966–1969.)

Ocean. Its unique geographical position, along with its complex terrain and diverse underlying surfaces (Zheng et al., 2013), results in a rich and varied natural geography. The country encompasses a wide range of landforms, including vast plateaus, plains, mountains, hills, and basins, contributing to the diversity of its physical environment. China's terrain is high in the west and low in the east, mainly showing a stepped distribution, from the Tibetan Plateau on the first step (average elevation above 4000 *m*) in the west to the basins and plateaus on the second step (average elevation of 1,000–2000 *m*) in the center and the plains, hills, and low mountains on the third step (average elevation below 500 *m*) in the east, with obvious terrain steps and complex topography (Figure 1). Meanwhile, many mountains in China are trending east-west and northeast-southwest, many of which play an important role and are often the dividing line between different topographic and climatic regions. The existence and differences of various topographical features make the combination of natural resources such as soil, moisture, and heat diverse.

China's vast territory extends approximately 73°E to 135°E in longitude and 18°N to 53°N in latitude. This expansive coverage, combined with significant variations in continental-maritime distances, mountain orientations, and topographic elevations, creates exceptionally complex climate patterns with highly diversified climatic resources. Looking at the type of climate, the eastern part is a monsoon zone (which includes temperate monsoon, subtropical monsoon and tropical monsoon climates), the northwestern part has a temperate continental zone, and the Tibetan Plateau is an alpine zone. Divided by temperature zones, there are the tropical, subtropical, warm temperate, middle

temperate, cold temperate, and Qinghai-Tibet Plateau zones. In terms of humid and arid areas, there are humid, semi-humid, semi-arid and arid areas. Where different wet and dry areas may belong to the same temperature zone; different temperature zones may belong to the same wet and dry area. Thus within the same climate type, there are differences in heat and dryness and humidity. The variability conferred by various elements of nature, human activities, and climate change always influences the climatic characteristics of different regions of China.

2.2 Study data

2.2.1 Meteorological data

The meteorological data used in this study were obtained from the China Surface Climate Data Daily Dataset (V3.0), covering observational records from 1966 to 2019. The dataset is accessible through the China Meteorological Administration's Data Sharing Service Platform (URL: http://data.cma.cn). This dataset includes daily observational data from 699 weather stations across China, covering the period from 1951 to the present. Key elements recorded in the dataset include station-level atmospheric pressure (0.1 hPa), air temperature (0.1 °C), relative humidity (1%), precipitation (0.1 mm), evaporation (0.1 mm), wind direction and speed (0.1 m/s), sunshine duration (0.1 h), and ground surface temperature at 0 cm (0.1 °C). The temperature and relative humidity data are derived from the average of four daily observations taken at 02:00, 08:00, 14:00, and 20:00.

The dataset employs a rigorous three-tiered quality control system ("Station-Provincial-National") to ensure data accuracy and completeness. Compared to earlier released surface meteorological datasets, this version demonstrated significantly improved data quality, with an effective data rate exceeding 99% for most meteorological elements and accuracy rates approaching 100%. These characteristics make it a highly reliable source for studying long-term climate changes and regional meteorological patterns. Moreover, the dataset's extensive spatial coverage and long temporal span offer well-preserved historical meteorological records, providing robust support for analyses of climatic variations across different regions and periods. These features render it an invaluable resource for research in fields such as agriculture, climatology, and ecology.

The data mainly involved in the paper are temperature, relative humidity, and precipitation. Due to objective reasons such as instrument failure and environmental factors, there are some stations with missing data, so to ensure data integrity and continuity, processing and screening are required before calculation and analysis. In case of missing data for a particular day from the continuous observations of the temporal period used in this paper, the average of the previous day and the next day is used instead to supplement them; linear interpolation using the values of the same date elements from neighboring stations when the continuous observations of the temporal period used are missing data for multiple days. If the interpolation rate is greater than 0.5% in the site data, the site is deleted. To meet the actual research needed, and eliminate the problems such as insufficient stations or regional errors brought by the division according to different administrative districts, therefore, this paper divides the area according to municipal administrative boundaries, and the distribution of its specific weather station locations are displayed in Figure 1.

2.2.2 Calendar data

Agrometeorological Proverbs, major solar terms, e.g., Wakening of Insects, Major Heat, as well as minor solar terms like the Dog Days, are frequently mentioned (Chen et al., 2022). To facilitate this study, it was necessary to compile and analyze the dates of these solar terms. The calendar data used in this research were sourced from the "Chinese Almanac Network" (https://www.rili.com.cn). The Twenty-Four Solar Terms are defined based on the sun's position along the ecliptic, reflecting the annual changes caused by Earth's revolution. Consequently, their dates on the Gregorian calendar are generally fixed, but slight annual variations of 2–3 days may occur. To enable cross-year comparisons, representative dates were assigned to each solar term (Ji et al., 2015). Specifically, if the date varied by 2 days across years, the last day was chosen as the representative date. For variations spanning 3 days, the middle date was selected (see Table 1). Due to the cumulative effects of Earth's orbital motion, some years witness the phenomenon of double Beginning of Spring, commonly referred to as "double Beginning of Spring of the Lunar Years". Other years are classified as "normal years" (see Table 2). Furthermore, differences between leap years and common years were addressed. Following the method of Qian et al. (2011), leap year data were adjusted by removing February 29. The value for February 28 was then replaced by the average of February 28 and February 29 to maintain continuity. This approach eliminates potential discrepancies caused by leap years while ensuring that the time series for each year has a uniform length, facilitating more robust data processing and analysis. Through these standardization methods, the solar term dates and yearly time series were harmonized, providing a solid foundation for investigating the scientific validity, regional applicability, and meteorological principles underlying agricultural proverbs.

The Dog Days, a minor solar term, represents the hottest and most humid, sultry period of the year. It is divided into the early, middle, and late phases, with the dates determined by the alignment of the Twenty-Four Solar Terms and the traditional Chinese Heavenly Stems (number:10) and Earthly Branches (number:12). The annual Dog Days begin with the Summer Solstice, one of the Twenty-Four Solar Terms in the traditional Chinese calendar. According to the ancient Chinese method of recording time using the heavenly stems and earthly branches, the Dog Days officially starts on the third Geng day following the Summer Solstice. This marks the onset of the first phase, known as Initial Fu. Each Geng day occurs 10 days apart, with the Initial Fu and Final Fu phases each lasting 10 days. However, the specific date of the third Geng day following the Summer Solstice varies annually, leading to differences in the duration of the Middle Fu phase, which can last either 10 or 20 days. Additionally, due to the annual variation in the timing of the Summer Solstice, the start date of the Dog Days differs across years. In summary, the start and duration of the Dog Days vary each year (Table 2), though the period generally falls between July and August (Xu, 2024). Due to the variability of the Dog Days, the study does not assign fixed representative dates for each phase of the Dog Days.

3 Methods

3.1 Least-square fitting

Due to the complexity and variability of climate factors in daily weather changes, temperature fluctuations are often large and difficult to predict. As a result, directly comparing and analyzing temperature data can be challenging, often leading to a lack of clear and direct comparisons between data points (see Figure 2). To address this issue, the article employs the least squares polynomial method (Gao et al., 2021) to fit a curve, highlighting the "RW" characteristic and illustrating the warming trend. Least squares polynomial fitting is a mathematical method designed to find the best approximation of a set of discrete data points by fitting a function. Geometrically, the method seeks a curve that minimizes the sum of squared distances between the data points and the fitted curve, aiming to reflect the basic trend or most closely approximate the variation pattern of the data. Since the fitting function is a polynomial, this method is referred to as polynomial fitting.

This study uses statistical data to obtain two time series of daily average temperatures over multiple years, representing the BSLY and NY, for the period from the Beginning of Spring to the Minor Heat (time period before Dog Days), with a duration of 155 days. Through multiple comparative analyses of the fitting results, it was found that a 5 best polynomial provided the best fit for the warming trend under study, with a correlation coefficient (R^2) of approximately 0.90, as confirmed by significance testing. Although the R^2 value slightly fluctuates for polynomial degrees higher than 5, the marginal benefit of the fitting results gradually diminishes. Therefore, a 5 polynomial fitting is chosen in this study (Figure 3).

It is important to note that due to significant differences in climate conditions, topography, and other factors across different regions of China, the warming trends exhibit considerable variation. Therefore, in analyzing the warming trends, this study establishes the following criteria for the cases where the warming rate in BSLY exceeds that in NY (Equation 1).

$$\left(d_{[(k_s/k_n)>1]}/d\right) \times 100\% > 65\% \tag{1}$$

In Equation 1, $d_{[(k_s/k_n)>1]}$ represents the number of days within a specific period during which the warming rate of BSLY exceeds that of NY, d denotes the total number of days in that period, k_s is the warming rate of BSLY, k_n is the warming rate of NY. This parameter allows for a quantitative comparison of the differences in temperature increase rates and their duration across different types of years.

3.2 Temperature-humidity index

Given the lack of modern precision measuring instruments in ancient times, the "heat" described in the proverb "The heat of Dog Days on double Beginning of Spring of the Lunar Years" primarily refers to the human perception of temperature, rather than just the air temperature values. Perceived temperature is influenced not only by temperature but also by factors such as humidity. Studies indicate that when the temperature falls within a comfortable range for the human body, changes in humidity have little effect on comfort levels. However, when the temperature exceeds or falls below the comfort zone, higher humidity levels can significantly impact the human body, causing discomfort, such as a feeling of stuffiness or chilliness (Ren, 2017). This effect is particularly evident under extreme weather conditions. For example, in the desert regions of northwest China, daytime temperatures can be extremely high, with dry air, while nighttime temperatures rapidly drop, creating significant diurnal temperature variation. In such cases, the changes in both humidity and temperature lead to a marked shift in perceived temperature, resulting in varying sensations of "heat".

Considering these factors, this study provides a more scientific analysis of the "DDH" characteristic by incorporating the Temperature-Humidity Index (THI) (Zhang C. et al., 2024). The THI integrates the daily maximum temperature, daily minimum temperature, and relative humidity to assess the temperature-humidity conditions and reflect human comfort levels. The concept of the THI was first introduced by Thom as the Discomfort Index (DI) (Thom, 1959), which was later widely adopted by the U.S. National Weather Service to evaluate summer comfort and work hours. The THI is not only applicable in the U.S., but can also be used in regions with latitudes similar to that of the U.S. (Giles et al., 1990), and it has been extensively applied in climate studies in China (Wang and Shen, 1998; Li et al., 2005; Wu et al., 2007). The THI provides a more accurate reflection of human thermal sensation, especially during hot summer months, where it is more sensitive to climatic variations.

This study analyzes the differences in the THI between BSLY and NY during the period from the beginning of spring to the Minor Heat, just prior to the Dag Days period. Specifically, the THI is used to measure the "Degree of Heat" characteristic of "DDH" in different years. By calculating the THI difference between BSLY and NY at various weather stations, this study further evaluates the variations in "Degree of Heat" between the two types of years (Formula 2, 3). The study also proposes a classification standard based on the THI for assessing the "Degree of Heat" and lists the corresponding criteria (Table 3), which quantitatively describe the "DDH" characteristics for different year types. In the context of intensifying global climate change, understanding and quantifying the impact of temperature and humidity changes on human comfort in different regions will be crucial for formulating more effective climate adaptation policies and mitigation strategies.

$$THI = K^{-1}\sum_{i=1}^{K} t_i - 0.55\left(1 - K^{-1}\sum_{i=1}^{K} x_i\right)\left(K^{-1}\sum_{i=1}^{K} t_i - 14.5\right) \tag{2}$$

$$D_j = THI_j^s - THI_j^n \tag{3}$$

Where, THI represents the Temperature-Humidity Index, t_i denotes the temperature on the *ith* day (unit: $^{\circ}C$), x_i denotes the relative humidity on the *ith* day (unit: 1%), with $i = 1,2 \ldots, K$, where K is the study period. D_j represents the difference in THI between two types of years. THI_j^s refers to the daily maximum or minimum temperature-based Temperature-Humidity Index for BSLY; THI_j^n refers to the daily maximum or minimum temperature-based THI for NY; $j = h, l$, where h represents the daily maximum temperature, l represents the daily minimum temperature.

4 Results and analysis

4.1 "Rapid warming" characteristic

This study presents four possible scenarios (Table 4) for the data fitting results based on the classification criteria, comparing the "RW" characteristic observed in the Beginning of Spring to Minor Heat period (time period before Dog Days) in BSLY years with the normal years. Combined with the proverb "The heat of Dog Days on double Beginning of Spring of the Lunar Years" compliance with the regional situation map (Figure 4) shows the geographic areas that meet and don't meet the characteristic of "RW", it can be seen that there is faster warming of BSLY than NY in most of the regions nationwide from 1966 to 2019, and the area of compliance accounted for 60.6% of China's area, where the warming temporal periods all occurred before the Spring Equinox, manifesting as different warming amplitude, durations, and temporal periods, and the main reason for the difference situation is the difference in the climate type and geographical topography to which they belong. The "RW" characteristic is divided as follows.

1. As shown in Figure 4, the regions exhibiting a pronounced "RW" characteristic are primarily located in southern China and the middle and lower reaches of the Yellow River, which together account for 35.8% of China's total land area. In these regions, during the periods from the Beginning of Spring to the Awakening of Insects (as shown in Figure 5A) and from the Beginning of Spring to the Spring Equinox (as shown in Figure 5B), the number of days where the warming rate of the BSLY exceeds that of NY accounts for more than 65% of the total days. This indicates that in these regions, the temperature rise in spring is faster, particularly due to the influx of warm, moist air from the ocean, which causes rapid warming (as shown in Figure 5A, e-m, days 1–14). Notably, at the Rain Water solar term (the 15th day after the Beginning of Spring, as shown in Figure 5: (A), m), vegetation begins to sprout. As the ancients observed, "The east wind thaws the ice, melting and turning it into water, which then becomes rain, hence the name Rain Water." This natural phenomenon reflects the climate characteristics of spring: with the input of warm air, the weather gradually warms, ice and snow melt, and precipitation increases, the warming speed during the Grain Rain solar term slows down. Scientifically, this phenomenon is closely related to the interaction between oceanic and continental air masses. During the Grain Rain period, the warm, moist air mass from the ocean becomes more active and engages in frequent and intense confrontations with the cold air masses from the continent. This interaction between the air masses not only causes fluctuations in temperature but also creates a boundary, or frontal zone, where the cold and warm air masses meet. This frontal zone leads to an increase in precipitation and a temporary drop in temperatures (Liang et al., 2023) (as shown in Figure 5: (A), m-n, days 15–22), as the competing air masses exert their influence on the region's weather patterns.

However, as the Awakening of Insects solar term begins, marking the first phenological period of the Twenty-Four Solar Terms, most regions experience the "season suitable for cultivation." At this stage, precipitation decreases compared to the Rain Water solar term, and temperatures enter a second round of accelerated warming (as shown in Figure 5: (A): n-f period, days 22–31, (B): n-f period, days 22–45). Two periods that meet the criteria are observed in this region, the cause of this phenomenon can be attributed to the influence of the monsoon system (Chen et al., 2022). The summer monsoon is primarily composed of the southeast monsoon from the Atlantic and the southwest monsoon from the Indian Ocean, which first make landfall in the region in early spring. Compared to other areas, the monsoon arrives earlier and stays longer in this region. As a result, in BSLY, especially during the spring, the rapid arrival of warm and moist air and its prolonged influence lead to a faster rise in temperature and a longer duration of the warming process. Therefore, during BSLY, this region experiences a faster and longer period of temperature increase compared to other areas.

2. In Figure 4, the regions with "RW" characteristic in moderate degree mainly include Xinjiang, Gansu, and western Inner Mongolia, accounting for 21.6% of China's area. In BSLY, the proportion of days when the slope of the warming curve exceeds that of NY is greater than 65%, and this occurs only during the period from the Beginning of Spring - Awakening of Insects. (Figure 6). This region has a temperate continental climate, which is far from the ocean and controlled by continental air masses all year round, resulting in hot summers with little precipitation and low winter temperatures due to Siberian High (Ding, 1990; Zhu et al., 2019; Huang et al., 2024). This region is located in the middle of the Asian and European continent, in early spring, part of the North Atlantic Current (Kuang et al., 2009) from the west coast of the continent will reach here across the flat European continent, increasing temperatures (Figure 6, e-m points, 1–12 days), yet the warming period is still influenced by the Siberian High (Li et al., 2024), which decreases temperatures (Figure 6, m-n points, 12–18 days). However, with the weakening of the Siberian High (Li et al., 2024) in early spring and the blockage of cold currents by topography such as the northwest-southeast trending Altai Mountains, the region experiences a slight, short-term temperature increase during the Beginning of Spring to Awakening of Insects period in BSLY.
3. In Figure 4, the regions with weak conformity of the "RW" characteristic mainly include Beijing, Tianjin, Liaoning, *etc.*, accounting for 3.2% of China's area. In BSLY, the period from the Beginning of Spring - Spring Equinox is the only time frame during which the proportion of days when the slope of the warming curve exceeds that of normal years is greater than 65% (Figure 7B). The region belongs to temperate monsoon climate, simultaneous rain and heat, influenced by the marine southeast monsoon, sufficient precipitation, but relative to the southern region in early spring is still influenced by cold currents from high latitudes Siberia (Huang et al., 2024), under the combined influence of the two air currents, the warming in the Rain Water stage is relatively slow (Figure 7A: m-n points, 14–25 days, (B): m-n points, 14–25 days), the warming takes a long time, the warming amplitude is slighter relative to regions with moderate and strong compliance (Figure 7A: m-f, 14–31 days). The warming trend becomes

apparent only when considering the entire Beginning of Spring to Vernal Equinox period.

4. Figure 4 indicates certain regions that do not meet the 65% classification standard (as shown in Figure 8) for the "RW" characteristic. These deviations are likely influenced by local topography and climatic conditions. The affected areas primarily include Heilongjiang, Jilin, eastern Inner Mongolia, the Qinghai-Tibet Plateau, and southern Yunnan, collectively covering 32.4% of China's total area. Among them, in Jilin, Heilongjiang, eastern Inner Mongol, *etc.*, the influence of the Siberian High (Huang et al., 2024) from the high-latitude in winter, cold and dry, while summer is affected by the southeast monsoon, high temperature and rain. Compared to other regions, the higher latitude of this area results in persistent influence from cold northwesterly monsoons originating from high-latitude regions after the Beginning of Spring. Simultaneously, the northeast-southwest-oriented Changbai Mountains block the warm and moist southeast airflow from the ocean, delaying its arrival in this region. These factors collectively contribute to minimal differences in temperature rise between the two types of years following the Beginning of Spring. These factors result in minimal differences in temperature increase between the two types of years after the Beginning of Spring. In addition, the Qinghai-Tibet Plateau (Danzeng et al., 2024), including Tibet and most of Qinghai, falls within a high-altitude cold region. Due to the high elevation, warm-moist air currents from the ocean have difficulty ascending, resulting in no significant warming trend during the early stages compared to other regions. The southern Yunnan region, located in a low-latitude tropical valley (Wang et al., 2024), is characterized by a lack of winter and relatively stable temperature variations. As a result, there is little difference between years, and the "RW" characteristic in BSLY is not as pronounced compared to normal year.

4.2 "Dog Days Heat" characteristic

This article categorizes the differences in the "Degree of Heat" during the Dog Days period between BSLY and NY from 1966 to 2019 according to the degree of conformity with the characteristics of "DDH," dividing them into three categories (as shown in Figure 4). In the figure, the regions showing a strong degree of conformity to the "DDH" characteristic represent areas in "BSLY" that experience more intense "DDH" heat compared to "NY". These areas are primarily located in China's subtropical monsoon zone (Wang Liping et al., 2021) (one of the five major climatic regions), which is basically in the southern part of China's geographical division, accounting for 67.2% of the southern region. These regions are influenced by the warm and moist airflows brought by the Pacific subtropical high, resulting in high summer temperatures and frequent rainfall. In July, the average temperature is approximately 28 °C, with certain areas surpassing 29 °C. Additionally, during July and August, the region is under the influence of the subtropical high pressure, resulting in frequent sunny days, long hours of sunshine, and a higher frequency of high temperatures. The research by Kong (2019) also indicates that the number of sauna days (characterized by prolonged high temperatures and "extended standby" conditions) in China shows a clear spatial differentiation, with higher values in the southeast and lower values in the northwest, and minimal differences across different decades. This phenomenon reveals the spatial imbalance in regional climate change in China, as well as the significant impact of regional climatic factors on the frequency and intensity of sauna days. In addition, the study by Xia et al. (2011) on the climate zoning of the Dog Days also points out that the Dog Days and Quasi-Dog Days areas are located south of 40°N in China, primarily influenced by the summer monsoon. These regions are relatively more aligned with the climatic conditions required by the second part of the traditional saying about summer "heat," making the subtropical areas in southern China particularly suitable for these conditions.

To comprehensively explore the factors behind the "DDH" in BSLY compared to NY in southern regions, and taking into account that rainfall can impact on temperature and relative humidity to a certain degree, the study analyzes and contrasts rainfall data during Dog Days time period for both types of years from 1966 to 2019 within the region. The results indicate that the rainfall during the Dog Days period in NY is generally higher than in BSLY. However, a detailed comparison across decades reveals that in the 1980s, the Dog Days period rainfall in BSLY exceeded that of NY (Figure 9). Specifically, the average rainfall during this period in BSLY was 219.5 mm, compared to 189 mm in NY. The anomalously high rainfall in BSLY during the 1980s may be attributed to the EI Niño phenomenon in 1982 (Gu et al., 2018; Wang Yini et al., 2021). The relatively low temperature will result from more precipitation in short periods. Additionally, the long-term average relative humidity during Dog Days period from 1966 to 2019 shows minimal differences between the two types of years in southern China (78.5% in NY and 78.4% in BSLY). Thus, the Temperature-Humidity Index suggests that rainfall may play a key role in amplifying the "DDH" during BSLY compared to NY across much of the southern region.

In Figure 4, regions with weak conformity to the "DDH" characteristic (covering 11% of the southern region) and those that do not conform (covering 12% of the southern region) are collectively identified as areas that don't satisfy the "DDH" characteristic. Compared to areas where climatic conditions don't meet the characteristics of "DDH," both areas with weaker and stronger conformity to these characteristics are located in the southern region. However, due to the influence of topography and terrain (Zheng et al., 2013), these areas in some cases do not fully exhibit the characteristics of "DDH." Among the areas with weak conformity mainly consist of two non-conforming parts: one includes regions influenced by mountain ranges, such as Jiangxi and Fujian, which are affected by the Wuyi Mountain range; Hunan and Hubei, influenced by the Xuefeng and Wushan mountain ranges; Ningguo City in Anhui Province, where the Tianmu Mountain exists in the southeast and the Huangshan Mountain range in the west; and Yangjiang City in Guangdong Province, which has the Tianlu Mountain in the northeast and the Yunwu Mountain in the northwest and is surrounded by mountains and water. The regions that do not exhibit the characteristics of "DDH" may be influenced by mountains, whose orientations are mostly northeast-southwest. This topography often blocks warm and moist airflows from the ocean, limiting the flow of air and the

distribution of rainfall. In mountainous areas, rainfall patterns are usually significantly influenced by the terrain. Generally, mountains receive more rainfall than flatlands, and the windward slopes receive more rainfall than the leeward slopes (Liu et al., 2017). For example, Huangshan and Tunxi in Anhui Province are close to each other, but the average annual precipitation in Huangshan is 633 mm more than Tunxi (2387 mm in Huangshan and 1754 mm in Tunxi), which results in a year-round lower temperature in Huangshan compared to the surrounding area. Secondly, the area affected (Zheng et al., 2013) by the type of terrain, in the Guangxi Zhuang Autonomous Region's Laibin City, Baise City, Jiangxi Province's Jingdezhen City, *etc.*, the topography of the area is mostly surrounded by high, middle low basin shape, and relatively little precipitation due to the closed topography, surrounded by high mountains, the oceanic warm and humid airflow is difficult to enter.

5 Discussions

Based on the analysis results of the two parts of the proverb in the article, it was found that conforming regions of the proverbs used in the article are overwhelmingly located in the southern region of the geographical zoning of China (Figure 4). These regions account for 15.9% of China's total area and 67.2% of the southern region. And the article selected "The heat of Dog Days on double Beginning of Spring of the Lunar Years" proverb is mainly spread in the Jiangsu, Zhejiang, and Shanghai area, Jiangsu, Zhejiang, and Shanghai area belong to the southern region, in the subtropical monsoon area (Wang Liping et al., 2021), rain and heat at the same time, the four seasons are distinct. The southern region has been the land of plenty since ancient times, the granary of Jiangnan, and farming civilization using the solar terms was relatively prosperous. This paper analyzes the meteorological knowledge behind the proverbs based on 54 years of meteorological data in China, and finds that the proverbs circulated in Jiangsu, Zhejiang, and Shanghai regions are consistent with the corresponding science, moreover, the analysis process of the proverbs shows that in the southern Yunnan river valley region, there is no winter all year round and the climate change is not significant, while in Jiangsu, Zhejiang and Shanghai regions, the four seasons are distinct, and the climate of the two regions has obvious differences, so in the verification result, the southern Yunnan river valley region does not conform to the proverb "The heat of Dog Days on double Beginning of Spring of the Lunar Years", and also shows that the applicability of the proverbs has regional characteristics. Therefore, based on various research findings, it can be concluded that the majority of the southern region of China, along with its climatic conditions, relatively meets the meteorological requirements outlined in the proverb. The analysis of the "The heat of Dog Days on double Beginning of Spring of the Lunar Years" proverb in this article reveals that China's vast territory is characterized by diverse climates across different regions. The proverb circulating in different places may only apply to areas with the same climate type, as well as the differences in topography and terrain may also have some influence to it, thus the proverb has certain regional and limitations.

This study examines the two characteristics of the proverb (The heat of Dog Days on double Beginning of Spring of the Lunar Years) "RW" and "DDH" to verify the scientific validity and regional applicability of the proverb. The study found that the regional classification of the proverb "RW" and "DDH" characteristics showed that the regions that conformed to them basically belonged to the southern region of China (Figure 4). Among them, the characteristic of the proverb that BSLY "RW" than NY has different results in different regions, depending on the degree of conformity, there is a difference between the warming period being within 31 days after the Beginning of Spring or within 46 days, and the difference may be due to the different climate types and geographical topography to which the different regions belong. In addition, in the characteristic of the proverb "DDH", BSLY is stronger than NY in terms of "Degree of Heat", which is mainly located in the southern region, covering 67.2% of the southern region. This is because the subtropical monsoon zone in southern China, in contrast to other regions, aligns with the climatic conditions necessary for the "DDH" characteristic as described in the proverb. Additionally, the proverb "RW" characteristic of the study found that in most of the regions in the early warming period, there will be a certain degree of cooling after the warming of the Beginning of Spring, which is often referred to as "late spring coldness" (Figure 5, 15–22 days), in which BSLY temperature fitting curve shows more obvious, NY temperature fitting curve shows not obvious relatively stable, and the cause of this cooling phenomenon or fluctuation phenomenon needs to be further explored. In a study of "DDH" characteristic of the proverb, it was also found that with global warming, the annual maximum temperature in most areas of China in recent decades began to occur during Minor Heat (Kong et al., 2021). In the latest Intergovernmental Panel on Climate Change (IPCC) sixth Report (IPCC, 2021), it is pointed out that the global average surface temperature has risen by 1 °C compared to pre-industrial levels. According to projections for the average temperature change over the next 20 years, global temperatures are likely to rise to or exceed 1.5 °C. The intensifying global warming directly affects the climate system, with a key manifestation being the increased frequency of extreme heat events (Zhou and Zhai, 2023). So the maximum temperature in the future may show an in advance phenomenon. Therefore, under the climate change, what kind of reasonable adjustment needs to be made to the agrometeorological proverbs in the future, how to combine them with modern science and technology by referring to the ancient experience, and how to modify and supplement them with the time, so that they can continue to be useful in modern agricultural production, also need to be further studied.

The findings of this study offer distinct scientific and practical contributions. On a scientific level, the research establishes a data-driven framework to quantitatively validate Traditional Ecological Knowledge. By successfully linking the lunar calendar phenomenon of Double Beginning of Spring to measurable thermal characteristics (Rapid Warming and Dog Days Heat), the study provides empirical evidence that moves beyond anecdotal accounts. This analytical approach can be applied as a template to systematically assess the validity of other agrometeorological proverbs worldwide. From a

practical standpoint, the results underscore the particular value of the lunar calendar and its associated proverbs for agricultural communities in developing regions with limited access to modern climate data. In the absence of high-resolution meteorological monitoring and advanced forecasting, these culturally rooted sayings function as an accessible, cost-free, and intuitively understood tool for planning farming activities. The demonstrated connection between the lunar calendar and seasonal climate dynamics in southern China suggests that it can offer reliable guidance for critical decisions, such as optimal sowing and harvest times. This inherent connection to local environmental cycles presents a key advantage over the purely astronomical solar calendar, especially in resource-limited settings.

Several considerations emerging from this work highlight productive pathways for future inquiry. First, our validation concentrated mainly on thermal and humidity variables. Expanding the analytical scope to include factors like extreme rainfall, solar radiation, and wind dynamics would yield a more integrated perspective on the agroclimatic intelligence contained in proverbs. Second, while our regional analysis confirms broad climatic correlations, the practical effectiveness of these proverbs depends on local context. Subsequent research should prioritize fine-scale, participatory studies with farmers to document how these sayings are actively used in management choices and to measure their impact on productivity and resilience. Finally, the accelerating pace of climate change introduces uncertainty into the stability of the historical relationships underpinning these proverbs. As baseline climate patterns evolve, the predictive power of traditional knowledge may require recalibration. A promising direction, therefore, is to create adaptive frameworks that merge the heuristic value of proverbs with contemporary climate data and forecasting tools, thus refining this cultural heritage for modern risk management applications.

6 Conclusion

This study, leveraging decadal meteorological datasets (1966–2019) on temperature, relative humidity, and rainfall, employs polynomial fitting and the Temperature-Humidity Index (THI) to decode the scientific basis of the agrometeorological proverb “Hot Dog Days in Lunar Years with Double Beginning of Spring”. Comparative climate modeling yields three key insights.

6.1 Proverbial model applicability and climate-resilient agriculture

The proverbial model demonstrated significant consistency with its traditional circulation zone (Jiangsu-Zhejiang-Shanghai) and extends to 15.9% of China’s territory (67.2% of southern regions), highlighting its adaptive capacity under climate change. Analysis of the “RW” phenomenon reveals that BSLY exhibit 23.5% more pronounced spring warming trends than NY, with RW zones covering 60.6% of China. Warming periods (31–46 days post-Beginning of Spring, all preceding the Spring Equinox) exhibit spatiotemporal dynamics: southern China and the middle-lower Yellow River show intense warming, while Xinjiang/Inner Mongolia demonstrate moderate responses. For DDH, 67.2% of southern China’s subtropical monsoon zones—characterized by synchronous temperature-rainfall increases—validate the proverb’s climatic predictability, underscoring its utility as a low-cost climate risk indicator for agroecosystems.

6.2 Integrating traditional knowledge into adaptive agricultural strategies

Scientific validation confirms that the empirical rules embedded in the proverbs largely align with region-specific atmospheric thermal-humidity coupling mechanisms. As adaptive tools rooted in millennial agricultural practices, Chinese Agrometeorological Proverbs require iterative scientific refinement under global warming. This study proposes a “time-adaptive, location-specific” framework for upgrading traditional models, enabling their integration into climate-smart practices. Such integration of ancient wisdom with modern climate science enhances their utility in guiding agrifood systems, reducing climate risks, and optimizing resource utilization.

6.3 Localized knowledge as complementary solutions for resilient agrifood systems

While proverbial models exhibit climate-zone specificity, their role in community-level adaptation is indispensable. As culturally embedded knowledge systems, they offer cost-effective risk mitigation for smallholder farmers—particularly in data-scarce regions where high-tech climate services are inaccessible. This study highlights the need to recognize traditional models as complementary to modern agronomy, advocating their inclusion in multi-tiered adaptation strategies. Such integration fosters resilient agrifood systems in developing regions, providing a scalable pathway toward sustainable agricultural transformation.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: URL: http://data.cma.cn, China Surface Climate Data Daily Dataset (V3.0).

Author contributions

SC: Conceptualization, Methodology, Writing – original draft. YH: Data curation, Validation, Investigation, Writing – review and editing. CS: Formal Analysis, Investigation, Software, Writing – review and editing. BS: Data curation, Formal analysis, Funding acquisition, Writing – review and editing. YS: Funding acquisition, Supervision, Writing – review and editing.

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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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AppendixGlossary of technical terms

Terminology	Definition in Plain Language
Agrometeorological Proverb	A traditional saying, based on long-term observation, that links weather or seasonal patterns to agricultural practices
Twenty-Four Solar Terms	A unique Chinese calendar system that divides the year into 24 periods, each reflecting specific seasonal climate changes and phenological events (e.g., Beginning of Spring, Winter Solstice)
lunar calendar	The traditional Chinese calendar, which is based on the Moon. It determines the dates of the Twenty-Four Solar Terms
Rapid Warming (RW)	In this study, it specifically refers to a significant and fast increase in temperature observed within a certain period (e.g., 31 or 46 days) after the "Beginning of Spring" in years with Double Beginning of Spring
Dog Days Heat (DDH)	In this study, it refers to the intensity of heat during the Dog Days period, measured using the Temperature-Humidity Index (THI)
Double-Beginning of Spring Lunar Years (BSLY)	Abbreviation for "Beginning of Spring in Lunar Years". Used in this paper to refer to years with the Double Beginning of Spring phenomenon
Normal Years (NY)	Abbreviation for "Normal Years". Used in this paper to refer to lunar years without the Double Beginning of Spring phenomenon, for comparison
Temperature-Humidity Index (THI)	A composite index that combines air temperature and relative humidity to quantify the perceived human comfort (or discomfort) caused by heat

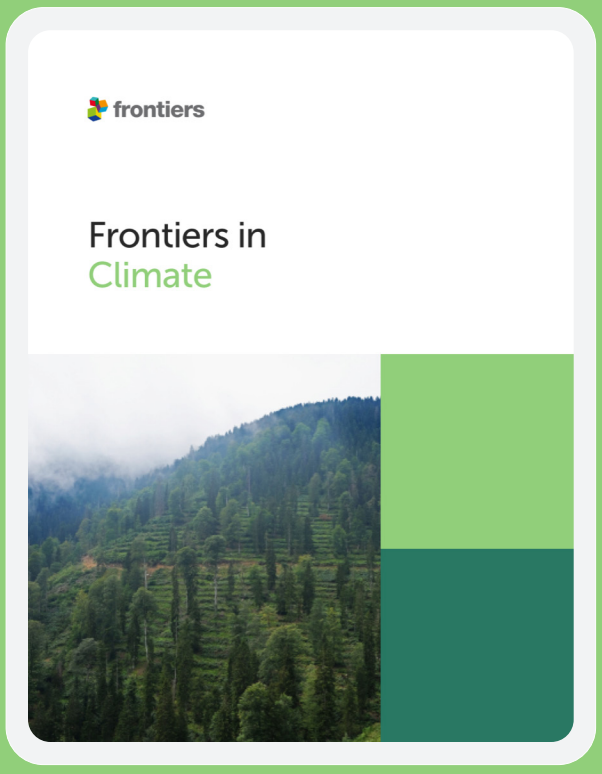
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