



Spatiotemporal patterns and spatial dislocation with economic level of China's ecological resilience

Zedong Yang^{ab}, Hui Sun^{ab*}, Xuechao Xia^{ab}, Xuefeng Zhang^{ab}

^a Xinjiang Innovation Management Research Center, Xinjiang University, Urumqi 830046, China

^b School of Economics and Management, Xinjiang University, Urumqi 830046, China

ARTICLE INFO

Keywords:

Ecological resilience
Economic level
Spatiotemporal pattern
Spatial dislocation

ABSTRACT

Ensuring a harmonious coexistence between man and nature is crucial for China's economic and social development. However, with increasing industrialization and urbanization, there is a growing mismatch between China's ecological resilience (ER) and economic level (EL) of development, which poses a notable social threat. Currently, the link between ER and EL in China remains unclear, especially in terms of spatial dislocation (SD), referring to the disconnect between the locations where environmental impacts occur and those where economic benefits or activities are concentrated. Therefore, this paper aims to provide theoretical support and an empirical basis for policy-based solutions to address this gap. Based on the SD theory, this study systematically discusses the temporal changes, spatial patterns, and SD characteristics of China's ER and EL using spatial auto-correlation and barycentric analysis to analyze data from 30 provinces covering the period 2011–2021. The key results are as follows. China's ER shows a general trend of growth; however, its distribution is uneven. The spatial pattern generally decreases from the southeastern coastal provinces to the northwest. Moreover, a gradually increasing positive correlation is observed between the ER and EL, but this correlation varies by region, with some showing regional linkages and others developing independently. Finally, the dislocation index of ER and EL presents divergent results based on region—the eastern and central regions primarily show a high level of dislocation, whereas the western and northeastern regions show a low level of dislocation. The results provide a comprehensive overview of the spatiotemporal patterns in the association between ER and EL in China. The results emphasize that to balance sustainable regional development and ecological governance, a region-specific approach must be employed, prioritizing innovation-driven strategies for high ER in more developed regions and market-oriented strategies in less developed regions.

1. Introduction

In the context of ecological resilience (ER) and the economic level (EL) of development, spatial dislocation (SD) refers to the separation between the locations where environmental impacts occur and the places where economic benefits or activities are concentrated. In large countries such as China, with substantial inter-regional differences, the uneven distribution of ecological degradation and economic gain is very concerning. Here, ER refers to an ecosystem's carrying capacity concerning external disturbances while maintaining a relatively stable structure and process, and serves as the core for a harmonious relationship between man and nature (Zhang and Li, 2018). With the continuous advancement of industrialization and urbanization, regional development has affected the ecological environment through population accumulation, economic development, and

energy consumption, resulting in a series of problems such as environmental pollution, resource shortage, and ecological damage. According to the IEA's International Energy Agency's *Carbon Dioxide Emissions Report* of 2022, China's CO₂ emissions in 2022 were approximately 11.48 billion tons. According to the Ministry of Ecology and Environment, the average concentrations of SO₂, PM_{2.5}, and NO₂ in 2022 were 9, 29, and 21 µg/m³, respectively. A large amount of carbon dioxide and pollutant emissions have brought great challenges to the ecological environment. Given these figures, China's 14th Five-Year Plan points out the necessity of continuously promoting the improvement of the ecological environment while strengthening its security. The State Council's (2023) *White Paper on China's Green Development in the New Era* further indicated the necessity of strengthening the protection and restoration of ecosystems. Therefore, the formation of a reasonable and logical pattern of ER across China has be-

* Corresponding author.

E-mail address: 15276512048@126.com (H. Sun)

<https://doi.org/10.1016/j.cjpre.2025.01.004>

Received 17 July 2024; Accepted 17 December 2024

2325-4262/© 2025 Shandong Normal University. Publishing services by Elsevier B.V. on behalf of KeAi Communications Co. Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

come an urgent issue. In particular, ER, as an important aspect of the harmonious coexistence of man and nature, is not only a result of socioeconomic development but a crucial determiner of future high-quality development.

A scientific understanding of the relationship between ER and EL is needed to achieve coordinated regional development. Therefore, the spatiotemporal patterns of ER are of vital significance for policymakers, including a detailed discussion on the relationship between ER and EL and the moderating factor of China's green development.

In recent years, ER and its relationship with EL have attracted increasing scholarly interest. So far, researches in related fields have mainly focused on three aspects. First, scholars have explored the spatiotemporal patterns of ER in China. Some scholars have found that China's urban ER in its eastern, central, and western regions show a trend of fluctuation and decline, with gradual stabilization (Li and Wang, 2023). In contrast, other researchers note that China's ER shows a slow growth trend despite fluctuations (Li et al., 2023). From the perspective of space, China's ER shows significant heterogeneity and aggregation, with it being higher in the southeast and lower in the northwest (Wang et al., 2023). For example, the ER level of the Pearl River Delta urban agglomeration is significantly lower than that of the Beijing–Tianjin–Hebei region and the Yangtze River Delta (Zhang et al., 2023). Moreover, in recent years, the ER of the coastal complex ecosystem in the East China Sea has shown a declining trend, with significant spatial heterogeneity and a sea-land gradient (Zhang et al., 2023). Meanwhile, in the Awang Basin, the social ER fluctuates moderately but does not linearly increase or decrease (He et al., 2021). China's transportation ER is generally low and decreases from the eastern regions to the western ones (Hu et al., 2021).

Second, researchers have examined the relationship between ER and other socioeconomic factors, finding a nonlinear relationship between landscape patterns and some elements of ER, such as water yield, soil retention, carbon sequestration and oxygen release, and grain production (Ma et al., 2023). Wang et al. (2023) found that, in the Chengdu–Chongqing economic circle, the coupling coordination of urban ER and new types of urbanization show trends of rapid but balanced growth. In the northern Tianshan Mountains, the comprehensive urbanization level shows a significant positive correlation with urban ER, with the number of double-high cities (with high ER and EL are high) increasing and double-low cities (with low ER and EL) decreasing (Wang et al., 2023). Meanwhile, the socioeconomic ER in the Yangtze River Economic Belt was found to be moderately imbalanced (Lin et al., 2022). In the Chengdu–Chongqing city cluster, the economic and social resilience of most cities lags behind the ER (Han et al., 2023). In the “new normal” following the COVID-19 pandemic, environmental resilience has been positively correlated with urban resilience (Fu et al., 2023).

Finally, scholars have explored the factors driving ER and its improvement. Galappaththi et al. (2017) showed that the entrepreneurial motivation of small-scale shrimp farmers did not have a significant impact on social and ecological resilience; however, in protected marine areas, social–ecosystem resilience varies with the scale of fishing (Bueno and Schiavetti, 2019). High-speed rail (Wang et al., 2023) and regional integration policies (Jiang and Jiang, 2024) have a negative impact on urban ER; however, industrial transformation has a positive impact (Tang et al., 2023). The ER of the Qinghai–Xizang Plateau is most significantly affected by temperature (Liu et al., 2023). Moreover, the construction of green infrastructure has been found to be an important factor in improving urban ER (Wu et al., 2020).

This provides a scientific basis and strategic suggestions for improving regional ER and promoting sustainable development. Despite the insights provided above, few scholars have explored the spatiotemporal patterns of ER and its relationship with EL at the provincial level based on SD. Therefore, based on the SD theory, this study uses

panel data from 30 Chinese provinces from 2011 to 2021 and an SD index model to explore the spatiotemporal patterns of ER and its relationship with EL. Initially, it was used to examine spatial differences in housing and employment opportunities of disadvantaged groups in the context of urban spatial reconstruction (Liu and Painter, 2012; Martin, 2001; Martin, 2004; Wang et al., 2011). In this study, it was used to investigate spatial differences between ER and EL. The study contributes to the literature in three major ways. First, it constructs a province-level evaluation index system for ER, enabling a comprehensive discussion of its spatiotemporal patterns. Second, the SD index model enables a detailed exploration of the relationship between ER and EL as informed by SD, contributing to the literature on ER. Third, in contrast to existing studies that overemphasize the presence of disturbances and the resilience of ecosystems (Wang and Niu, 2023), the social nature of ER is emphasized.

2. Methods

2.1. Spatial auto-correlation

2.1.1. Global spatial auto-correlation

This study used global spatial auto-correlation to analyze the spatial correlation of ER on a global scale, represented by the global Moran's I index, whose calculation formula is detailed in the references (Dong et al., 2023; Ping et al., 2004; Ren et al., 2020).

2.1.2. Local spatial auto-correlation

Local spatial auto-correlation was used to reflect the degree of correlation between micro-spatial units and their neighboring units on a certain attribute value in local space (Flahaut et al., 2003; Premo, 2004).

2.2. Analysis of barycenter and space overlap

The barycenter is the moment equilibrium point of the spatial distribution of nodes. This study used a barycentric analysis model to calculate the SD barycenter of ER and EL and reveal the relationship between them according to their dynamic evolution. Its expression is detailed in the references (Guerin et al., 2021; Li et al., 2016; Li et al., 2023; Ling et al., 2022; Wang et al., 2018).

The spatial overlap is used to investigate the spatial coupling between the ER and EL barycenters in China, and is expressed using the distances between the centers of gravity; the closer the distance, the greater the overlap (Kain, 1968).

2.3. SD index

Kain proposed the SD theory in the 1960s; initially, it was used to examine spatial differences in housing and employment opportunities of disadvantaged groups in the context of urban spatial reconstruction (Liu and Painter, 2012; Martin, 2001; Martin, 2004; Wang et al., 2011). We introduced the SD index in this study to explore the spatial equilibrium development status of ER and EL in China. The SD and contribution indices constructed in this study are detailed in the references (Liu and Painter, 2012; Martin, 2001; Martin, 2004; Wang et al., 2011). Among them, the contribution indices are the ratio of the absolute value of the spatial dislocation index of the province and the sum of the absolute value of the spatial dislocation index of all provinces in the current year.

2.4. Index system construction

The existing literature overemphasizes the existence of disturbances and the self-resilience of ecosystems, ignoring their social attributes. This makes it difficult to comprehensively evaluate the es-

sential factors and innovative development ability of ER. From the perspective of evolutionary resilience, ER is an inherent attribute of an ecosystem. Regardless of whether the ecosystem is disturbed or not, it always has the dynamic ability to defend against disturbances before they occur, respond in time when disturbances occur, and continue to learn and innovate (Wang and Niu, 2023). Based on this concept, we proposed three stages of ER, namely, resistance, response, and innovation, based on which we constructed an ER index system (Table 1). First, resistance depends on conditioned endowments formed before the disturbance, manifested as the ecosystem’s ability to withstand disturbances and stabilize the structure. Therefore, this study considers ecological factors such as water, soil, and biological resources. Second, the response indicates that in the process of disturbance, rapid and diverse measures are adopted as a response to the shock, and an ecosystem’s response ability emphasizes the coping measures of active subjects to disturbances. Finally, an ecosystem’s innovation ability is its ability to respond rapidly to disturbances through learning, innovating, achieving breakthroughs, and updating the structure. In this context, the development of an ecosystem’s resilience is primarily embedded in its innovation ability, which includes the intensity, output, and input of innovations. Based on the evaluation index system, this study used the entropy weight method to synthesize the comprehensive value of the ER level of China’s provinces.

Table 1
Construction of ER evaluation index system

Primary index	Secondary index
Resistance	Total water resources (billion cubic meters)
	Urban park green area (ha)
	Green coverage rate of urban built-up areas (%)
	Forest coverage (%)
	Comprehensive utilization of general industrial solid waste (10 000 tons)
Responsiveness	Centralized treatment rate of sewage treatment plant (%)
	Harmless treatment rate of domestic waste (%)
ER	Fiscal expenditure on energy conservation and environmental protection (100 million yuan)
	R&D personnel full-time equivalent (man-year)
	R&D expenditure intensity (%)
	Number of green and low-carbon technology patent applications
Innovation ability	Number of university students per 100 000 population (persons)

2.5. Data sources

ER and EL data were mainly retrieved from the *China Statistical Yearbook*, *China Environmental Statistical Yearbook*, *China Science and Technology Statistical Yearbook*, and the China Economic Network from 2012 to 2022. Furthermore, the number of patent applications for green and low-carbon technology was retrieved from Green and low-carbon technology patent application data from the China National Knowledge Infrastructure patent analysis database, including fossil-fuel-certified energy reduction technology; energy conservation, recovery, and utilization; clean energy; energy storage; and greenhouse gas capture, utilization, and storage. All maps were based on the standard base map (GS(2023)2762) of the standard map Service System of the Ministry of Natural Resources, and the base map was not modified. All analysis was conducted using ArcGIS (Version 10.8).

3. Results and discussions

3.1. Spatiotemporal patterns of ER in China

3.1.1. Overall spatial pattern characteristics

Using ArcGIS10.8, we visually expressed China’s ER for the years 2011, 2016, and 2021, divided into gradients from large to small using natural breakpoints (Figure 1). Overall, China’s ER shows a growth trend. Moreover, the spatial pattern shows decreasing ER from the southeast coast to the northwest inland, bounded by the Hu Huanyong line.

In 2011, provinces with the first ER gradient included Beijing, Shandong, Jiangsu, Zhejiang, and Guangdong, accounting for about 16.67% of the land mass. Second-gradient provinces included Liaoning, Hebei, Shaanxi, Sichuan, Chongqing, Henan, Anhui, Shanghai, Hubei, Hunan, Jiangxi, Fujian, and Yunnan, accounting for 43.33%. The third gradient contained Heilongjiang, Jilin, Inner Mongolia, Shanxi, Tianjin, and Guangxi, accounting for 20%. Other provinces in the fourth gradient accounted for 20%. In 2016, the first-gradient provinces included Beijing, Shandong, Jiangsu, Zhejiang, and Guangdong (16.67%). Second-gradient provinces included Hebei, Henan, Sichuan, Yunnan, Hubei, Hunan, Anhui, Jiangxi, Fujian, Guangxi, and Shanghai (36.67%). Third-gradient provinces included Heilongjiang, Jilin, Liaoning, Inner Mongolia, Tianjin, Shanxi, Shaanxi, Chongqing, and Guizhou (30%). Fourth-gradient provinces accounted for 16.67%. Meanwhile, in 2021, the first-gradient provinces included Shandong, Jiangsu, Zhejiang, and Guangdong (13.33%), second-gradient provinces included Beijing, Hebei, Henan, Shaanxi, Sichuan, Anhui, Hubei, Hunan, Jiangxi, and Fujian (33.33%), third-gradient provinces included Heilongjiang, Jilin, Liaoning, Inner Mongolia, Tianjin, Shanxi, Chongqing, Guizhou, Guangxi, Yunnan, and Shanghai (36.67%), and fourth-gradient provinces accounted for 16.67%.

The temporal changes in ER can be explained as follows. First, government departments have actively promoted environmental protection and ecological restoration (e.g., *Action Plan for the Prevention and Control of Air Pollution*, *Action Plan for the Prevention and Control of Water Pollution*, and *Several Opinions on Delineating and Strictly Observing the Red Line for Ecological Protection*). Second, China has also implemented a series of national-level ecological protection projects to protect the northern glaciers and wetlands and restore degraded ecosystems. Third, the government continues to promote urbanization, ecological restoration, and general “greening” to improve the stability of urban ecosystems. Fourth, scientific and technological innovation has been promoted and supplemented with a focus on education. Fifth, the public awareness of environmental protection has increased, and most citizens actively participate in environmental protection actions.

The spatial pattern of ER can be explained as follows. First, China’s natural environment is very complicated. The southeast region has undulating mountains, abundant water resources, and high vegetation coverage, whereas the northwest region has a dry climate with a fragile ecological environment. Second, the southeast coastal areas have also experienced large-scale industrialization and urbanization after the reform and opening up, creating new ecological and environmental challenges such as industrial emissions and municipal waste. However, these areas enjoy strong economic growth, allowing governments and businesses to embrace ecological and environmental protection. In contrast, the northwest inland region has suffered significant ecological damage due to extensive mineral and energy exploitation, and its EL is relatively low. Third, the Chinese government has applied different policies on ecological environment protection and restoration in different regions. For example, the southeast region is more highly regulated than the northwest. Fourth, under the background of “green development”, tourism and ecological agriculture have become an important part of the economic development of South and Southwest China, providing a protective effect on the eco-

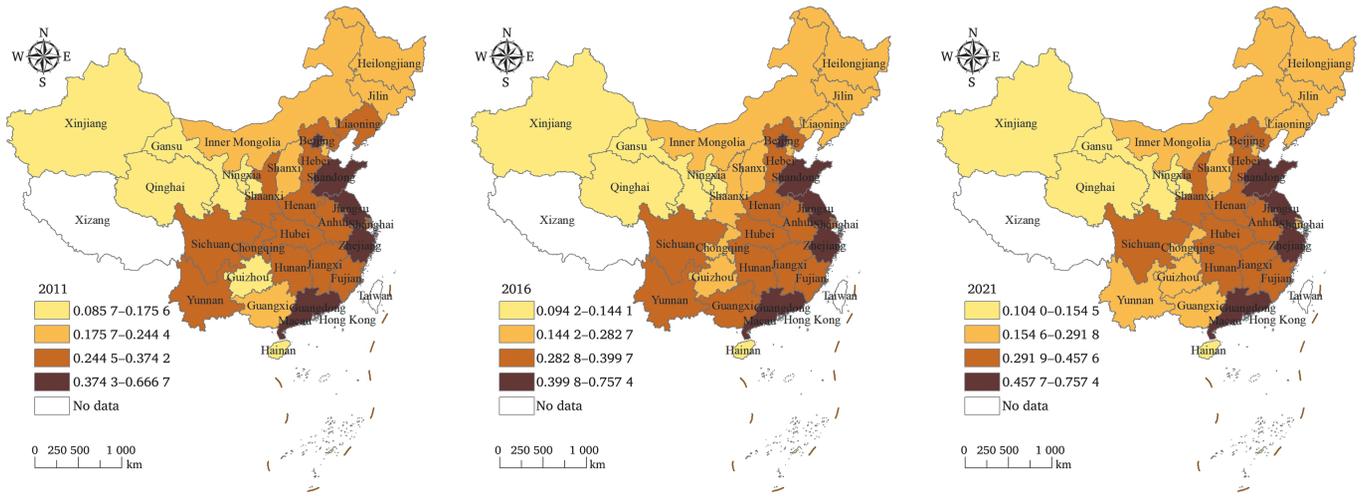


Figure 1. Overall spatial pattern of ER in China from 2011 to 2021

Notes: The maps were based on the standard base map (GS(2023)2762) of the standard map Service System of the Ministry of Natural Resources, and the base map was not modified.

logical environment.

3.1.2. Spatial correlation pattern characteristics of ER

Although the above text analyzed the trends and distribution of provincial ER in China from the spatiotemporal dimension, it did not reflect the spatial correlation characteristics of ER. Therefore, this study further adopted global spatial auto-correlation to calculate the global Moran’s *I* index of provincial ER in China (Table 2). In 2012 and 2014, the index was 0.092 and 0.098, respectively, and both were significant at the 10% level. In 2016, the index was 0.121, which was significant at the 5% level. In 2018 and 2020, the values were nonsignificant. Thus, in the early periods, the spatial distribution of high- and low-value ER areas showed significant spatial aggregations and positive correlations. That is, regions with high or low ER were clustered, and the ER among neighboring provinces had spill-over effects. Later in the study period, there were no significant spatial aggregations.

Table 2
Spatial auto-correlation: Moran’s *I* index of ER from 2011 to 2021

Year	2012	2014	2016	2018	2020
Moran’s <i>I</i>	0.092*	0.098*	0.121**	0.016	0.070
<i>P</i> value	0.088	0.077	0.037	0.492	0.155

Note: **, and * indicate that Moran’s *I* is significant at 5%, and 10% levels, respectively.

Additional analysis showed that the ER of China’s provinces has changed from “regional linkages” to “independent development.” First, during the early study period, to achieve economic growth and social development, provinces generally adopted a regional linkage model, where different provinces are closely connected in resource allocation, industrial cooperation, and economic cooperation. Through regional linkages, provinces could borrow from each other and leverage their advantages, thereby improving overall economic benefits and development levels. Second, with the rapid development of China’s overall economy, provincial strength and competitiveness gradually increased. Some provinces accumulated rich resources and advantageous industries and demonstrated substantial innovations and market competitiveness, which explains the relatively independent development trend. Based on these findings, more developed regions should attend to independent development and actively explore development models and roads suitable

for local development.

Using ArcGIS10.8 software, we analyzed the local spatial auto-correlation characteristics of ER in China and drew a local-indicators-of-spatial-association map (Figure 2). As can be seen from Figure 2, China’s ER in 2011 demonstrated high–high (H–H) clustering in Shandong, Jiangsu, Shanghai, Zhejiang, Anhui, and Fujian (i.e., both the province and its neighbors had high ER). Meanwhile, in Jiangxi, low–high (L–H) clustering was observed (i.e., the provincial ER was low, but the neighbor’s ER was higher). H–L clustering was seen in Sichuan province, and L–L clustering was seen in Qinghai and Gansu. In 2016, H–H clustering was observed in Jiangsu, Zhejiang, Anhui, Jiangxi, Fujian, and Hubei, L–H clustering was seen in Henan and Shanghai, H–L was seen in Sichuan province, and L–L clustering was seen in Xinjiang, Qinghai, and Gansu. In 2021, H–H clustering was seen in Jiangsu, Zhejiang, Anhui, Jiangxi, Fujian, and Hubei, L–H clustering was seen in Shanghai, H–L clustering was seen in Sichuan, and L–L clustering was seen in Xinjiang, Qinghai, and Gansu.

There was a high level of aggregation in the eastern and central regions, but some provinces had low ER because the geographical diffusion in the high-level aggregation area was not fully developed. A low aggregation area emerged in the western region, but some provinces had high ER. That is, the low-level aggregation area did not establish learning and knowledge-tracking mechanisms. As such, the ER in China is characterized by a double aggregation of high and low levels that tends to be differentiated among regions. First, the eastern and central regions have superior geographical locations, good natural conditions, and strong advantages in economic and cultural development, as well as favorable climate. As such, their natural ecosystem is resilient. Moreover, these regions receive more investments and policy support for infrastructure construction, key industries, and ecological protection. The implementation of these policies has driven the development of local industries and an improved ecological environment, enhancing its ER. Furthermore, in the course of China’s historical development, the eastern and central regions have always played important roles as economic and cultural centers, whereas the western region has remained in a relatively backward state due to its geographical location and natural conditions. In recent years, many people have moved into the western region, but the population of the eastern and central regions has remained relatively stable, which has led to the ER of the eastern and central regions being higher than that of the western region.

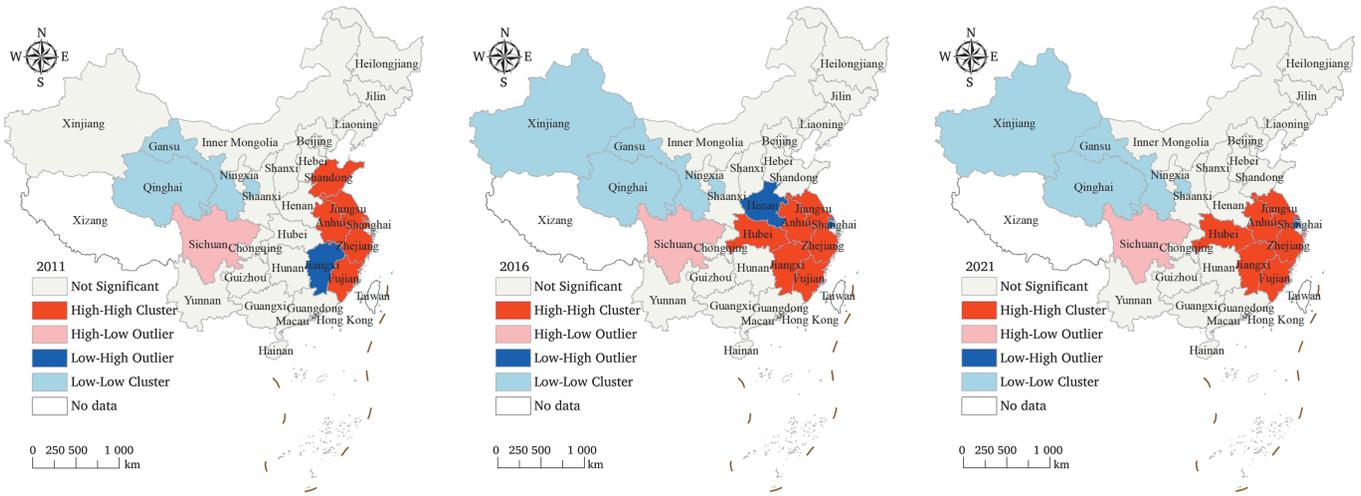


Figure 2. Spatial correlation pattern of ER in China from 2011 to 2021

Note: The maps were based on the standard base map (GS(2023)2762) of the standard map Service System of the Ministry of Natural Resources, and the base map was not modified.

3.3. SD between ER and EL in China

3.2.1. Spatiotemporal relationships between ER and EL

We conducted Pearson correlation analysis on the ER and EL in China, finding a significant positive correlation with a yearly rising trend, from 0.885 in 2011 to 0.951 in 2021. However, the rate of the correlation coefficient is slow, indicating a significant positive correlation between the ER of China’s provinces and their EL, with the relationship becoming stronger, albeit with a slow rate of improvement. Therefore, clarifying the evolution characteristics of this dislocation relationship is crucial to provide a reference for coordinated regional development and the adjustment and optimization of relevant policies and measures.

Subsequently, barycenter and spatial overlap methods were used to quantitatively reveal the spatial inconsistencies between provincial ER and EL, and the center of gravity and dislocation distance in each study year were calculated using ArcGIS10.8 (Table 3). The results are as follows. From 2011 to 2021, the center of gravity of ER in China varied between 113° 74'E–113° 82'E and 32° 77'N–32° 92'N, showing a migration trajectory of northeast → southwest → northwest. The center of gravity of EL was between 114°45'E–114°93'E and 32° 01'N–32° 65'N, showing a migration trajectory of northeast → southwest → southwest. By comparing the displacement linkages, we found that the change trend of the center of gravity of ER and EL demonstrated consistency as both showed general characteristics of moving westward movement; however, substantial differences were observed in the distribution position, transfer path, transfer distance, and speed in each period. Most notably, the center of gravity of EL is always located to the southeast of the ER, and the westward movement of EL is greater.

China has a vast territory, and there are obvious differences in the distribution of natural resources. Most are found in the western regions, whereas economic development is mainly concentrated in the East. Due to the demand for resources in the East, the economic cen-

ter of gravity has gradually moved west. However, due to the dense traffic and population in the eastern region, a relatively stable development foundation has been established; therefore, the EL center of gravity is always located to the southeast of the ER center of gravity. Moreover, the Chinese government has consistently advocated for green development, and under this framework, it has continuously promoted ecological protection and sustainable development in the western region through policies and financial investments, due to which the barycenter of ER has moved to the west.

Additionally, the eastern region’s first-mover advantage and superior economic foundation have generated the necessary investments to develop industries. Furthermore, China’s geographical conditions are different in different regions, such as terrain, climate, and water resources. Due to the limitations of the geographical environment, there is limited space for economic development and resource utilization in the eastern region, resulting in the economic center of gravity moving to the west. Further, the western region has a relatively large carrying capacity, which is conducive to the development and protection of the ecological environment. Finally, from the perspective of dislocation distance, the barycenter dislocation distance between ER and EL has a positive U-shaped change trend over time. The distance decreased from 132.08 km in 2011 to 111.41 km in 2016 and then to 137.37 km in 2021.

In the early development stage, China’s EL was relatively low, with a relatively small impact on the ecological environment. Therefore, the barycenters of EL and ER were relatively close. Next, with the rapid development of China’s economy, the speed of the movement of the economic center of gravity to the west gradually accelerated compared with that of the ER center of gravity, which has led to an increase in dislocation distance. With increasingly prominent ecological and environmental problems, government departments have gradually realized the importance of sustainable development and taken relevant measures, such as adjusting the economic structure and implementing environmental policies. Therefore, the EL and ER centers of gravity movements have tended to become stable, with the dislocation distance reducing. Therefore, the dislocation and separation trend between ER and EL in China exists but is gradually easing.

Table 3

Distribution and dislocation of ER and EL gravity centers

Year	ER gravity center		EL gravity center		Dislocation distance (km)
	Longitude	Latitude	Longitude	Latitude	
2011	113°82'E	33°18'N	114°93'E	32°65'N	132.08
2016	113°81'E	32°77'N	114°85'E	32°53'N	111.41
2021	113°74'E	32°92'N	114°45'E	32°01'N	137.37

3.2.2. Characteristics of SD patterns between ER and EL

Correlation and barycentric analyses can only provide a macro perspective; they cannot explain local dislocation intensities and distribution modes. Therefore, we applied the SD index to each region to quantitatively reveal the SD phenomenon and its effect on the degree

of ER and EL

The overall dislocation pattern from 2011 to 2021 was assessed using ArcGIS10.8. We divided the average SD index value of Chinese provincial units into 11 research years and 4 grades based on the natural break-point classification method (Figure 3). The dislocation index showed a clear positive regional differentiation pattern ($SMI > 0$), where ER lagged behind the EL. There were 19 negative dislocation regions ($SMI < 0$) where EL lagged behind ER. Notably, the dislocation pattern agreed with the spatial pattern of ER, with positive dislocation regions with high dislocation indices mainly concentrated in eastern and central regions. Although the eastern and central regions had relatively high ER, they lagged behind their EL. Thus, it is necessary to continue to improve regional ER to match the EL and give full play to the supporting role of EL in ER. Meanwhile, negative dislocation regions with a low dislocation index were widely distributed in the western and northeastern regions, indicating that the EL of these regions lagged significantly behind their ER. Thus, increasing efforts to undertake industrial transfers and accelerating the economy will be necessary.

The evolution of the dislocation pattern from 2011 to 2021 was assessed by dividing the SD indices of Chinese provincial units into three research years and four grades based on the natural break-point classification method (Figure 4). The results indicate that the dislocation index of ER and EL shows obvious regional differences, with a generally stable differentiation pattern. The positive dislocation areas were mainly in the eastern coastal provinces (e.g., Hebei, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, and Guangdong) and central provinces (e.g., Henan, Hubei, and Hunan). In western China, only Sichuan had a positive dislocation. Additionally, the dislocation index of the eastern coastal region was larger than that of the central region. Although the eastern coastal region had a high ER, it lagged behind EL, with a high degree of dislocation. Compared with the southeast coastal region, the ER of the central region was lower. The negative dislocation area was mainly distributed in the western, northeast, and parts of the central region. First, the eastern coastal area has a superior geographical location and good transportation conditions, which attracts investment and industry and therefore rapid economic development. However, this situation also causes heavy resource consumption and environmental pressures. Second, the eastern coastal region plays an important role in China’s national development strategy and has generally received more policy support and financial investments. This includes infrastructure construction, economic-opening policies, and industrial transfers. Third, the eastern coastal re-

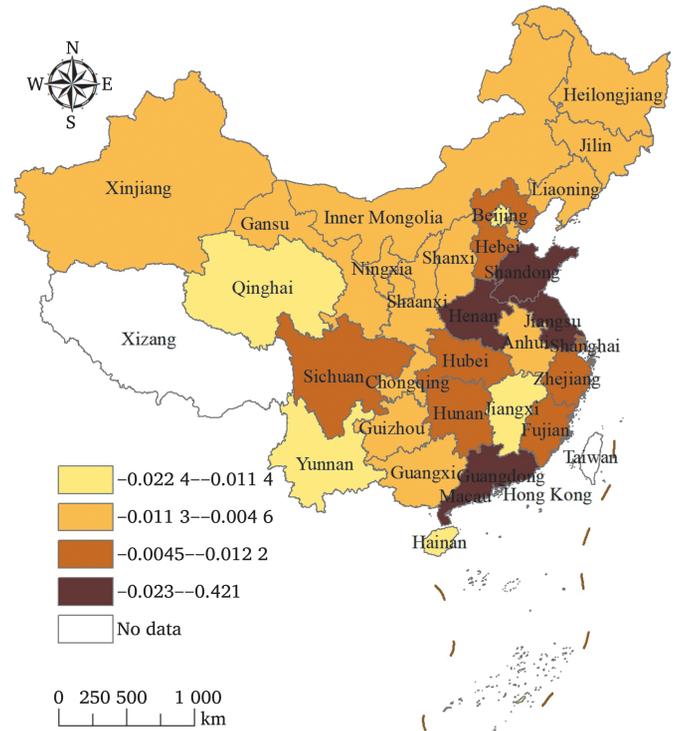


Figure 3. Overall dislocation pattern between ER and EL in China
Notes: The maps were based on the standard base map (GS(2023)2762) of the standard map Service System of the Ministry of Natural Resources, and the base map was not modified.

gion underwent earlier economic development, resulting in a high level of urbanization, a strong economic foundation, and resource advantages. By contrast, the western, northeast, and central regions lag in economic development and face challenges such as inadequate infrastructure and industrial layout.

This study also assessed the patterns in the contribution rate of dislocation from 2011 to 2021, where the contribution rates of the SD index of Chinese provincial units were split across three study years and divided into four levels based on the natural break-point classification method (Figure 5). The contribution rate of the eastern coastal

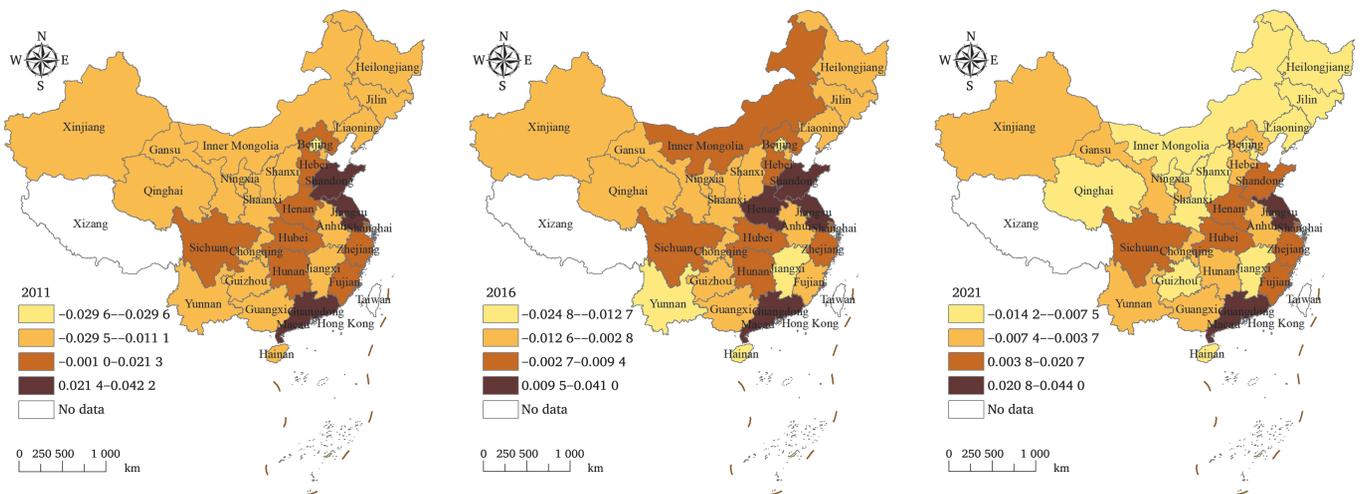


Figure 4. Dislocation pattern between ER and EL in China from 2011 to 2021
Notes: The maps were based on the standard base map (GS(2023)2762) of the standard map Service System of the Ministry of Natural Resources, and the base map was not modified.

region is the highest, followed by the western and central regions. After calculating the standard deviations and coefficients of variation, we found that the standard deviation and coefficient of variation decreased from 0.030 3 to 0.026 6 and 0.908 7 to 0.798 3, respectively, from 2011 to 2021. This shows that each research unit's contribution rate was balanced over time, and the polarization phenomenon was significantly alleviated. Figure 5 also shows that regions with a higher contribution rate gradually spread from the eastern and western regions to the central regions. This phenomenon is primarily caused by the SD between ER and EL in some research units. In summary, the ER of the eastern coastal region lags behind its EL, resulting in a strong positive dislocation, resulting in the highest contribution rate of dislocation. Meanwhile, as the EL lags behind the ER in the western region, a negative dislocation is observed, with the next-highest contribution rate. Finally, the contribution rate of dislocation in the central region was the lowest because the ER and EL were relatively balanced. The possible explanations for this phenomenon are as follows. First, the eastern coastal region plays an important role in China's economic development, gathering considerable investments and innovation resources, and it has an established industrial chain and market system. In contrast, the economic foundation of the western region is relatively weak with a low level of development. In this regard, the central region has moderate economic strength. These differences in economic development have led to the highest contribution rate being observed in the eastern coastal regions. Second, the eastern coastal areas have relatively rich natural and industrial resources, including marine resources and transportation and logistics advantages compared to the central region, where resource allocation and the industrial structure are relatively balanced, and the western region, which has scarce resources. Third, the eastern coastal region has strong capabilities and attractiveness in scientific and technological innovation and industrial upgrading, providing strong support for economic development. Moreover, this region has been supported by a series of fiscal, tax, and industrial development policies, which have promoted its economic development and innovation capacity. In contrast, the western and central regions lag in terms of policy support and regional planning. Finally, although the eastern coastal areas are developing rapidly, they also face problems such as industrial pollution, land use pressure, and resource shortages. As the western and central regions are relatively less industrial and dense in terms of population, and possess more abundant ecological and resource conditions, they face fewer ecological and environmental problems.

In general, compared with the existing studies that only analyzed

the spatiotemporal evolution characteristics of ER (He et al., 2021; Hu X et al. 2021; Li and Wang, 2023; Li et al., 2023; Wang et al., 2023; Zhang et al., 2023; Zhang et al., 2023), this study further clarified its spatial correlation characteristics and its spatial dislocation relationship with EL, which is conducive to guiding the coordinated development of ecological environment and economic level.

4. Conclusions and policy implications

4.1. Conclusions

Our study systematically addressed the temporal changes, spatial patterns, and SD characteristics of China's ER and EL using spatial auto-correlation, barycentric analysis, and SD index model. We found that China's ER is growing overall, and the spatial pattern decreases from the southeast to the northwest regions, bounded by the Hu Huanyong line. The provincial ER values are characterized by a shift from regional linkages to independent development, presenting high and low aggregation characteristics. High aggregation exists in the eastern and central regions, whereas in the western regions, a low-level gathering area was formed, indicating differentiation among regions. A significant positive correlation is observed between provincial ER and EL; however, the improvement speed is slow. Both centers of gravity show a general westward movement. However, their migration distribution, transfer path, transfer distance, and speed differ considerably. Most noticeably, the EL center of gravity is always located to the southeast of the ER, presenting a positive U-shaped trend over time, where positive dislocation regions with high dislocation indices are primarily concentrated in the eastern and central regions. Meanwhile, negative dislocation regions are widely distributed in the western and northeastern regions. Finally, the ER of the eastern coastal region lags behind its EL, resulting in a strong positive dislocation. As such, the contribution rate of dislocation is the highest in that region. In the western regions, the EL lags behind its ER, which leads to negative dislocation. Meanwhile, the contribution rate of dislocation in the central region is the lowest because the ER and EL are relatively balanced.

4.2. Policy implications

ER is crucial for the modernization of the harmonious coexistence between man and nature in China. From the perspective of sustainable development, China's strategic goal is to coordinate and syn-

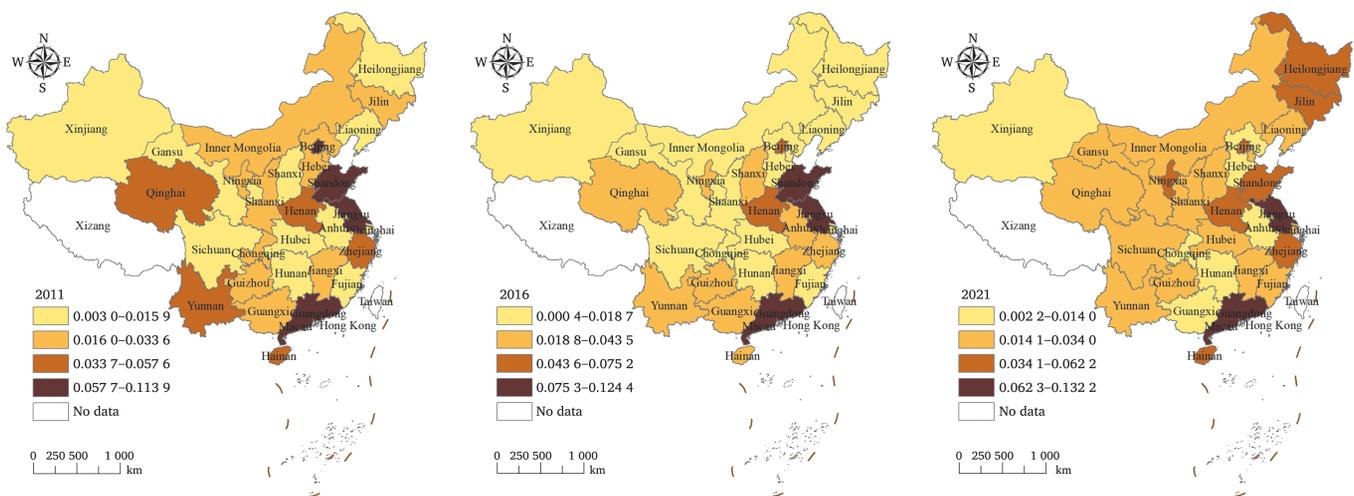


Figure 5. Evolution of contribution pattern of SD in China from 2011 to 2021

Notes: The maps were based on the standard base map (GS(2023)2762) of the standard map Service System of the Ministry of Natural Resources, and the base map was not modified.

chronize ER and EL and maintain this synchronization. Compared with previous studies (Liu and Painter, 2012; Wang et al., 2011), this study uses provincial-level data to provide a holistic geographical scale analysis, and our SD model allows us to systematically investigate the SD characteristics of ER and EL, illuminating existing problems in the coordination relationship between ER and EL at a spatial level. The findings hold significant implications for government departments in the formulation of relevant policies and measures. Specifically, the policy implications of this study are as follows. First, ER tends to lag behind EL in relatively developed areas such as the eastern coastal region. In this regard, policymakers should focus on adhering to high-quality development, with innovation at the center. Besides, ensuring continued economic development with industrial transformation and upgrading, realizing efficient operations of the economic system, and providing fundamental guarantees for the ultimate improvement of ER are crucial. In this process, with the increase in demand for technological solutions, personnel training and green and low-carbon technological innovations must be strengthened.

Second, the EL in western and other relatively underdeveloped regions lags behind their ER. In these regions, traditional development modes of resource exploitation for economic growth should be updated. Moreover, market forces and competition should be introduced to give full play to the reshaping effect of the market on location and promote the formation of the geographical agglomeration of enterprises and industries in regions with resource endowments. Moreover, the integration of national and global industrial systems should be prioritized to create new sources of economic growth, where market-oriented transformations will stimulate the vitality of regional green and low-carbon innovations.

Data availability

Data will be made available on request.

Disclosure statement

No potential conflicts of interest were reported by the authors.

Authorship contribution statement

Zedong Yang: Original manuscript authorship, data collection, data analysis, study design, formal analysis, visualization, draft revision, writing review, and editing. Hui Sun: Original manuscript authorship, study design, formal analysis, draft revision, reviewing, and editing. Xuechao Xia: Original manuscript authorship, data analysis, study design, formal analysis, draft revision, reviewing, and editing. Xuefeng Zhang: Original manuscript authorship, data analysis, study design, formal analysis, draft revision, reviewing, and editing.

Funding

The study was funded by the National Natural Science Foundation of China [Grant No. 71963030], a subproject of China's third comprehensive scientific expedition to Xinjiang [Grant No. SQ2021xjkk01800], a major science and technology project in the Xinjiang Uygur Autonomous Region [Grant No. 2022A01003], and a scientific research innovation project for excellent doctoral students of Xinjiang University [Grant No. XJU2022BS010].

References

- Bueno, P.F., Schiavetti, A., 2019. The influence of fisherman scale in the resilience of socio-ecological systems: an analysis using Q methodology. *Ocean & Coastal Management* 169, 214–224.
- Dong, Y.H., Peng, F.L., Li, H., Men, Y.Q., 2023. Spatial autocorrelation and spatial heterogeneity of underground parking space development in Chinese megacities based on multisource open data. *Applied Geography* 153, 102897.
- Flahaut, B., Mouchart, M., San Martin, E., Thomas, I., 2003. The local spatial autocorrelation and the kernel method for identifying black zones. A comparative approach. *Accident; Analysis and Prevention* 35, 991–1004.
- Fu, H.Y., Hong, N.N., Liao, C., 2023. Spatio-temporal patterns of Chinese urban recovery and system resilience under the pandemic new normal. *Cities* 140, 104385.
- Galappaththi, I.M., Galappaththi, E.K., Kodithuwakku, S.S., 2017. Can start-up motives influence social-ecological resilience in community-based entrepreneurship setting? Case of coastal shrimp farmers in Sri Lanka. *Marine Policy* 86, 156–163.
- Guerin, L., Vieira, J.G.V., de Oliveira, R.L.M., de Oliveira, L.K., de Miranda Vieira, H.E., Dabanc, L., 2021. The geography of warehouses in the São Paulo Metropolitan Region and contributing factors to this spatial distribution. *Journal of Transport Geography* 91, 102976.
- Han, S., Wang, B., Ao, Y.B., Bahmani, H., Chai, B.B., 2023. The coupling and coordination degree of urban resilience system: a case study of the Chengdu–Chongqing urban agglomeration. *Environmental Impact Assessment Review* 101, 107145.
- He, S.T., Wang, D.J., Li, Y., Zhao, P., Lan, H.J., Chen, W.L., Jamali, A.A., Chen, X.Q., 2021. Social-ecological system resilience of debris flow alluvial fans in the Awang Basin, China. *Journal of Environmental Management* 286, 112230.
- Hu, X.W., Su, Y.Q., Ren, K.F., Song, F., Xue, R.X., 2021. Measurement and influencing factors of urban traffic ecological resilience in developing countries: a case study of 31 Chinese cities. *Regional Sustainability* 2, 211–223.
- Jiang, N.N., Jiang, W., 2024. How does regional integration policy affect urban resilience? Evidence from urban agglomeration in China. *Environmental Impact Assessment Review* 104, 107298.
- Kain, J.F., 1968. Housing segregation, Negro employment, and metropolitan decentralization. *The Quarterly Journal of Economics* 82, 175–197.
- Li, D.H., Yang, J.M., Hu, T.Z., Wang, G.F., Cushman, S.A., Wang, X.Y., László, K., Su, R., Yuan, L.F., Li, B.P., Wu, Y.W., Bai, T., 2023. The seeds of ecological recovery in urbanization—Spatiotemporal evolution of ecological resiliency of Dianchi Lake Basin, China. *Ecological Indicators* 153, 110431.
- Li, D., Yang, W.P., Huang, R.Y., 2023. The multidimensional differences and driving forces of ecological environment resilience in China. *Environmental Impact Assessment Review* 98, 106954.
- Li, G.Z., Wang, L.Q., 2023. Study of regional variations and convergence in ecological resilience of Chinese cities. *Ecological Indicators* 154, 110667.
- Li, M.S., Ren, X.X., Zhou, L., Zhang, F.Y., 2016. Spatial mismatch between pollutant emission and environmental quality in China—a case study of NOx. *Atmospheric Pollution Research* 7, 294–302.
- Lin, Y.Z., Peng, C., Chen, P., Zhang, M.J., 2022. Conflict or synergy? Analysis of economic-social- infrastructure-ecological resilience and their coupling coordination in the Yangtze River economic Belt, China. *Ecological Indicators* 142, 109194.
- Ling, M.H., Guo, X.M., Shi, X.L., Han, H.B., 2022. Temporal and spatial evolution of drought in Haihe River Basin from 1960 to 2020. *Ecological Indicators* 138, 108809.
- Liu, C.Y., Painter, G., 2012. Immigrant settlement and employment suburbanisation in the US. *Urban Studies* 49, 979–1002.
- Liu, L.N., Zhang, Z.C., Ding, S.H., Yang, F., Fu, T.R., 2023. Combined effects of climate change on urban resilience in the Tibetan Plateau. *Environmental Impact Assessment Review* 102, 107186.
- Ma, X.B., Zhang, J.H., Wang, P.J., Zhou, L.Y., Sun, Y., 2023. Estimating the nonlinear response of landscape patterns to ecological resilience using a random forest algorithm: evidence from the Yangtze River Delta. *Ecological Indicators* 153, 110409.
- Martin, R.W., 2001. The adjustment of black residents to metropolitan employment shifts: how persistent is spatial mismatch? *Journal of Urban Economics* 50, 52–76.
- Martin, R.W., 2004. Spatial mismatch and the structure of American metropolitan areas, 1970–2000. *Journal of Regional Science* 44, 467–488.
- Ministry of Ecology and Environment, 2023. Report of the Ministry of Ecology and Environment on the state of national ambient air quality in December and January–December 2022. Beijing: Ministry of Ecology and Environment, 2023. (in Chinese)
- Ping, J.L., Green, C.J., Zartman, R.E., Bronson, K.F., 2004. Exploring spatial dependence of cotton yield using global and local autocorrelation statistics. *Field Crops Research* 89, 219–236.
- Premo, L.S., 2004. Local spatial autocorrelation statistics quantify multi-scale patterns in distributional data: an example from the Maya Lowlands. *Journal of Archaeological Science* 31, 855–866.
- Ren, H.R., Shang, Y.J., Zhang, S., 2020. Measuring the spatiotemporal variations of vegetation net primary productivity in Inner Mongolia using spatial autocorrelation. *Ecological Indicators* 112, 106108.
- Tang, D.C., Li, J.N., Zhao, Z.Q., Boamah, V., Lansana, D.D., 2023. The influence of industrial structure transformation on urban resilience based on 110 prefecture-level cities in the Yangtze River. *Sustainable Cities and Society* 96, 104621.
- Wang S.M., Niu J.L., 2023. Study on the co-evolution of tourism economy and urban ecological resilience in Shandong Province. *Acta Geographica Sinica* 78(10):2591–2608. (in Chinese)
- Wang, E.R., Song, J.P., Xu, T., 2011. From “spatial bond” to “spatial mismatch”: an assessment of changing jobs–housing relationship in Beijing. *Habitat International* 35, 398–409.
- Wang, J., Wang, J.M., Zhang, J.N., 2023. Spatial distribution characteristics of natural ecological resilience in China. *Journal of Environmental Management* 342, 118133.
- Wang, J.Y., Zhang, Z.W., Liu, Y.S., 2018. Spatial shifts in grain production increases in China and implications for food security. *Land Use Policy* 74, 204–213.

- Wang, K.L., Jiang, W., Miao, Z., 2023. Impact of high-speed railway on urban resilience in China: does urban innovation matter? *Socio-Economic Planning Sciences* 87, 101607.
- Wang, K.W., Ma, H.T., Fang, C.L., 2023. The relationship evolution between urbanization and urban ecological resilience in the Northern Slope Economic Belt of Tianshan Mountains, China. *Sustainable Cities and Society* 97, 104783.
- Wang, L., Yuan, M.K., Li, H.L., Chen, X.D., 2023. Exploring the coupling coordination of urban ecological resilience and new-type urbanization: the case of China's Chengdu–Chongqing Economic Circle. *Environmental Technology & Innovation* 32, 103372.
- Wu, X., Zhang, J.J., Geng, X.L., Wang, T., Wang, K., Liu, S.D., 2020. Increasing green infrastructure-based ecological resilience in urban systems: a perspective from locating ecological and disturbance sources in a resource-based city. *Sustainable Cities and Society* 61, 102354.
- Zhang, H.T., Liu, Y.C., Li, J.L., Tian, P., Zhong, J., Gong, H.B., 2023. Evaluation and analysis of coastal complex ecological resilience based on multidimensional data: a case study of East China Sea. *Ecological Indicators* 155, 110981.
- Zhang, T., Sun, Y.X., Zhang, X.B., Yin, L., Zhang, B.L., 2023. Potential heterogeneity of urban ecological resilience and urbanization in multiple urban agglomerations from a landscape perspective. *Journal of Environmental Management* 342, 118129.
- Zhang, X.L., Li, H., 2018. Urban resilience and urban sustainability: what we know and what do not know? *Cities* 72, 141–148.