



OPEN

## Spatiotemporal patterns and typological differences in the development-protection nexus of resource-based cities in China

Li Ji<sup>1</sup>, Huadong Gao<sup>2</sup>✉, Longgao Chen<sup>3</sup> & Jihong Dong<sup>4</sup>

Resource-based cities (RBCs) are pivotal regions for China to achieve low-carbon development, and their transition performance is closely linked to territorial space development and protection (TSDP). To scientifically assess their sustainable development levels, this study constructed a comprehensive evaluation system for territorial space development and protection level (TSDPL), encompassing dual dimensions of development and protection. Based on panel data from 110 Chinese RBCs between 2005 and 2020, we systematically measured the spatiotemporal evolution of TSDPL for each city. The findings reveal that the TSDPL increased at an average annual rate of 2.791% during the period. However, the protection level consistently lagged behind the development intensity, reflecting an overall characteristic of prioritizing development over protection. Spatially, TSDPL exhibited a gradient differentiation pattern of being "higher in the southeast and lower in the northwest." Its center of gravity shifted approximately 51 km to the southwest, forming "high-high" agglomeration areas represented by Shandong and Jiangsu provinces and "low-low" agglomeration areas represented by Gansu Province. The absolute disparity in TSDPL among cities continued to widen, indicating a pronounced polarization trend. The research further uncovered significant heterogeneity in the transition outcomes: regenerative type cities, non-metallic-based cities, and those in the eastern region performed better, while growth type cities, forestry-based cities, and those in the western region lagged relatively behind. This suggests that under similar resource constraints, local development pathways and governance efficacy are key determinants of transition outcomes. By establishing a nationwide comprehensive TSDPL measurement framework, this study systematically identified the differentiated transition trajectories of RBCs across various development stages, dominant resource types, and regional contexts. It provides a scientific basis for implementing categorized guidance and targeted policies for low-carbon transition and spatial governance.

**Keywords** Resource-based cities, Territorial space development and protection, Measurement index system, Spatiotemporal evolution, Different types of cities

Resource-based cities (RBCs) refer to cities where the extraction, processing, and utilization of natural resources such as minerals and forests constitute the leading industries, accounting for approximately 40% of the total number of cities in China<sup>1</sup>. This study is based on China's "National Sustainable Development Plan for Resource-based Cities (2013–2020)" (hereinafter referred to as "the Plan"), which includes 126 prefecture-level RBCs. Considering administrative division adjustments and data availability, 110 prefecture-level cities were ultimately selected as the research sample. It should be noted that the Plan does not cover marine RBCs; therefore, the scope of this study is explicitly limited to land-based mining and forestry RBCs.

Low-carbon development has become a global consensus. RBCs are generally characterized by intensive territorial space development activities, such as large-scale resource extraction and rapid expansion of construction land<sup>2</sup>, and exhibit typical features of high energy consumption, high carbon emissions, and high pollution<sup>3–5</sup>. At the same time, environmental issues triggered by territorial space development compel cities

<sup>1</sup>School of Economics and Management, Wenzhou University of Technology, Wenzhou 325027, China. <sup>2</sup>College of Architecture and Energy Engineering, Wenzhou University of Technology, Wenzhou 325027, China. <sup>3</sup>School of Public Policy and Management, China University of Mining and Technology, Xuzhou 221116, China. <sup>4</sup>School of Environment and Spatial Informatics, China University of Mining and Technology, Xuzhou 221116, China. ✉email: 20240120@wzut.edu.cn

to implement territorial space protection measures, including ecosystem conservation and pollution control, which help reduce carbon emissions. Therefore, the low-carbon transition of RBCs is thus intrinsically linked to TSDP. TSDP influences urban carbon budgets through the structure, intensity, and changes in land use, as well as through the modes of human activity it supports<sup>6</sup>. Establishing a sound TSDPL measurement index system for RBCs and analyzing the spatiotemporal evolution of TSDPL are essential prerequisites for proposing effective low-carbon transition pathways for these cities.

Existing theoretical and practical studies on TSDP in RBCs remain limited. Current research primarily focuses on ecological conservation, restoration, and spatial planning strategies. Few studies have directly undertaken a comprehensive measurement of TSDPL. Commonly, scholars use development intensity to represent the territorial space development dimension, while aspects such as environmental protection, pollution control, and resource conservation are employed to reflect the level of territorial space protection.

Research on measuring the territorial space development level has often focused on the related concept of territorial space development intensity. Most scholars measure this intensity using a single indicator, typically the proportion of urban construction land to total area<sup>7–9</sup>, or alternatively, metrics like building density and height<sup>10,11</sup>. In multi-index studies, scholars from different disciplines (e.g., land use, urban planning) establish distinct indicator systems tailored to their specific research objects and purposes. Tan et al.<sup>12</sup> selected indicators from aspects of development scale, development benefit and development intensity to measure land development intensity. Tang et al.<sup>13</sup> used development density, industrialization and urbanization level to measure territorial space development intensity in the Yangtze River Basin. Zhou et al.<sup>14</sup> believed that land development intensity should include four aspects: development degree, development benefit, resource feedback effect and ecological environment governance. Liu<sup>15</sup>, Hu<sup>16</sup> and Zhu et al.<sup>17</sup> selected indicators from three aspects: population agglomeration capacity, land expansion degree and economic development intensity, and respectively measured and evaluated territorial space development intensity in China, the Three Gorges Reservoir area and Ma'anshan City. Based on the aforementioned literature, Wu<sup>18</sup>, Yang<sup>19</sup>, Chen et al.<sup>20</sup> considered the factor of social input, and selected indicators from four aspects to measure territorial space development intensity. The measurement of territorial space development intensity has been explored across diverse scales, from national and regional (e.g., Yangtze River Delta, Pearl River Delta) down to provincial, city, district, and county levels. Commonly used measurement methods include the entropy method<sup>12</sup>, Delphi method<sup>15</sup>, analytic hierarchy process<sup>21</sup> and principal component analysis<sup>18</sup>.

Direct measurement of the territorial space protection level is rare in the literature. Research attention has instead been devoted primarily to the quantitative measurement of environmental protection and resource conservation and utilization. From the perspective of environmental governance and ecological protection, Zhang et al.<sup>22</sup> selected six indicators, including the standard rate of industrial wastewater discharge, the comprehensive utilization rate of industrial solid waste and the standard rate of ground water quality, to construct the index system of environmental protection level. Zhuang et al.<sup>23</sup> selected four indicators to measure the environmental protection level of Chongming Island: the proportion of clean energy use, the standard rate of pollutant discharge of industrial enterprises, the rate of urban sewage treatment, and the proportion of environmental protection input in GDP. Many scholars also classify environmental governance and pollution control as the content of ecological environmental protection. Guo et al.<sup>24</sup> measured the level of ecological environmental protection from three aspects: ecological environmental pressure, current situation and treatment. Xu<sup>25</sup> selected 12 indicators from the four dimensions of ecological construction, treatment, pollution and resources to build an index system. Some scholars directly selected indicators by focusing on the proportion of nature reserves area, the green coverage rate, and the reduction and treatment of pollutant emissions. Although there are quantitative differences in indicators, the content expressed is similar<sup>26,27</sup>. In terms of measuring the level of resource conservation and utilization, Li et al.<sup>28</sup> selected indicators from the aspects of resource output, waste utilization and resource recycling. Zhang et al.<sup>29</sup> selected six indicators from the utilization of energy and public resources, including energy consumption per unit of GDP, public green space area per capita and road area per capita. Cheng et al.<sup>30</sup> believed that when measuring the level of energy conservation and utilization, it is necessary to pay attention to both the macro efficiency of energy and the substitution relationship between traditional energy and clean energy.

This study aims to construct a systematic analytical framework to bridge gaps in existing research, contributing to knowledge in three key aspects. First, it shifts the research perspective from singular, static assessments to a long-term, dynamic evaluation of the synergy between development and protection—a dimension previously underexplored in unified frameworks. Second, it deepens the understanding of heterogeneity within RBCs by systematically examining TSDPL variations across development stages, resource types, and regions, moving beyond the homogeneous or typologically narrow approaches of prior studies. This challenges “resource determinism” and highlights the role of differentiated local pathways and governance. Third, it connects macro-pattern characterization with meso- and micro-level mechanism exploration. Beyond describing the spatial patterns of TSDPL, it reveals a widening inter-city gap and polarization trend through kernel density and gravity shift analysis, providing targeted empirical evidence for investigating the underlying drivers of these disparities.

## Theoretical connotation and measurement system Definition of the connotation of TSDP in RBCs

### *The concept of TSDP*

Territorial space is a complex system integrating resources, population, economy, and environment. Evolving from a traditional focus on socio-economic benefits, territorial space development now, under the imperative of green and low-carbon development, integrates ecological and environmental protection as a core concern<sup>31</sup>. The concept of TSDP, originating from the 18th National Congress of the CPC, is a Chinese policy paradigm advocating for the simultaneous pursuit of development and protection. Policy analysis indicates that development

mainly entails resource exploitation, population agglomeration, and economic growth, most visibly through construction land expansion. Protection, in contrast, focuses on ecosystem conservation, pollution control, and resource conservation.

#### *The content of TSDP in RBCs*

Internationally, typical RBCs or regions, such as Germany's Ruhr region and the Rust Belt in the United States, have faced numerous challenges in areas such as socioeconomic profiles, ecosystem services, urbanization, and economic transformation during the process of deindustrialization<sup>32–35</sup>. Based on their economic development model, which relies heavily on the large-scale exploitation of natural resources, RBCs are particularly susceptible to environmental issues such as the discharge of "the three industrial wastes," as well as land occupation and degradation<sup>5,6</sup>. As a result, ecological restoration and pollution control have become focal and challenging aspects of spatial construction in these cities<sup>8,9</sup>. The connotations of TSDP in RBCs can be summarized as follows (Fig. 1):

- (1) For RBCs, territorial space development involves resource exploitation alongside land development, economic growth, and population aggregation. Land serves as the central component, characterized by the reclamation of unused land and the renewal of used land. This concept should not be equated with land use. Rather, territorial space development is defined by the transformation of land use types or modes, most notably the conversion of non-construction land into construction land. The quintessential indicators of this process are the expansion of construction land and the concomitant reduction of cultivated, forest, and grassland. Given that cultivated land exhibits stronger ecological functions than construction land, its conversion from ecological land (e.g., unused land, forest, grassland<sup>19</sup>) constitutes a development activity that degrades ecological integrity, thereby justifying the inclusion of both construction land and cultivated land within the measurement of territorial space development in this study.
- (2) Territorial space protection constitutes a policy framework aimed at maintaining ecological integrity and sustainable resource use. Its scope includes: ① ecosystem protection, namely the conservation of natural ecological lands like forests, grasslands, and wetlands; ② pollution control, involving the treatment of environmental pollutants in the air, water, and soil; and ③ resource conservation, which focuses on reducing consumption intensity and improving utilization efficiency for vital resources such as water, land, and energy.

#### **Construction of TSDPL measurement index system for RBCs**

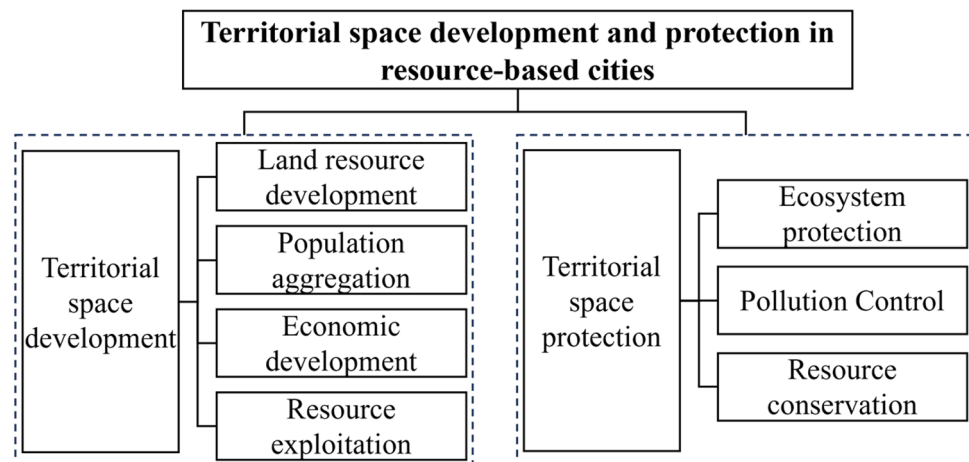
Based on the connotative analysis of TSDP in RBC, and guided by the principles of systematicity, data availability, representativeness, relative independence, as well as the integration of universality and specificity, this study constructs a TSDPL measurement index system comprising 7 factors and 22 indicators, drawing upon existing academic research. The detailed framework is presented in Table 1.

The designation of indicator polarities (positive/negative) in this study follows the policy orientation and research consensus regarding the low-carbon transition of RBCs. The specific rationale is as follows:

**Proportion of secondary industry (positive):** In RBCs, the secondary industry serves as the primary pillar for economic growth, employment, and fiscal revenue. An increase in its proportion is considered a key indicator of economic vitality and development intensity.

**Density of road network (positive):** A higher road network density represents more developed transportation infrastructure, which effectively supports economic agglomeration and spatial accessibility, making it a crucial metric for measuring development levels.

**Proportion of cultivated land area (positive):** Under the current stringent cultivated land protection policies, cultivated land possesses both productive and ecological functions. The preservation of its area is viewed as an important objective of territorial space protection, reflecting the rational utilization of limited spatial resources.



**Fig. 1.** Composition of TSDP in RBCs.

First-level indicators	Second-level indicators	Third-level indicators (unit)	Interpretation of indicators	Nature of indicators	References
Territorial space development	Land resource development	Proportion of construction land area (%)	Proportion of construction land area in total city area	+	19,20
		Proportion of cultivated land area (%)	Proportion of cultivated land area in total city area	+	
		Density of road network (km <sup>2</sup> /km <sup>2</sup> )	Proportion of total road area in total city area at the end of the year	+	
	Population aggregation	Total population (ten thousand)	Total resident population of the city at the end of the year	+	15,20
		Population density (person/km <sup>2</sup> )	Ratio of total resident population to total city area	+	
		Urbanization rate (%)	Proportion of urban population in total permanent resident population	+	
	Economic development	GDP (100 million yuan)	The gross national product of the city	+	20,36
		Annual income per capita (Yuan)	Average annual salary of on-the-job workers in the city	+	
		Annual consumption per capita (Yuan)	Ratio of the total value of social consumer goods to the total resident population of the city	+	
		Proportion of secondary industry (%)	Proportion of the output value of the secondary industry in the city's gross national product	+	
	Resource exploitation	Proportion of employment personnel in the mining industry (%)	Proportion of employment in mining in total employment	-	/
Proportion of investment in fixed assets in the mining industry (%)		Proportion of fixed asset investment in mining in total fixed asset investment	-		
Territorial space protection	Ecosystem protection	Proportion of forest area (%)	Proportion of forest area in total city area	+	30
		Proportion of water and wetland area (%)	Proportion of water and wetland area in total city area	+	
		Green coverage rate of built-up area (%)	Proportion of the green coverage area in the built-up area to the total area of the built-up area	+	
	Pollution control	Harmless treatment rate of household garbage (%)	Proportion of harmless disposal volume of household garbage in total household garbage	+	25
		Sewage treatment rate (%)	Proportion of sewage treatment volume in total sewage discharge	+	
		Comprehensive utilization rate of industrial solid waste (%)	Proportion of total amount of industrial solid waste utilized in total amount of industrial solid waste	+	
	Resource conservation	Energy consumption per unit of GDP (ton of standard coal/ten thousand yuan)	Ratio of total energy consumption to the city's gross national product	-	26,30
		Water consumption per unit of GDP (m <sup>3</sup> /ten thousand yuan)	Ratio of total water use to the city's gross national product	-	
		Output per unit of land (ten thousand yuan/km <sup>2</sup> )	Ratio of gross national product to total city area	+	

**Table 1.** Index system for measuring TSDPL in RBC. + represents a positive indicator and - represents a negative indicator.

Proportion of employment personnel/investment in fixed assets in the mining industry (negative): This indicator directly reflects the degree of a city's economic dependence on resource extraction. Over-reliance is a core manifestation of RBCs falling into the "resource curse" and facing transition difficulties. Setting this indicator as negative aims to encourage industrial diversification and embodies the value orientation of this study toward promoting transition.

## Overview of the study area, data sources and research methods

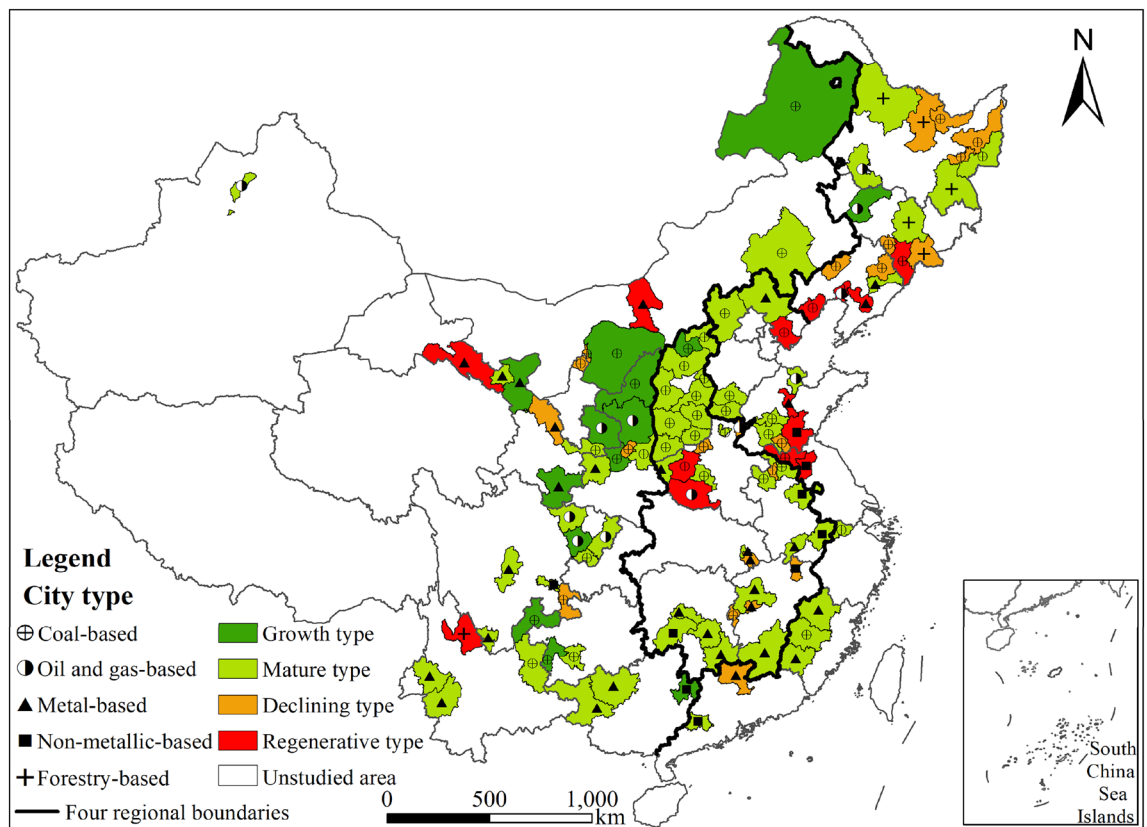
### Study area and city type classification

This study focuses on 110 prefecture-level RBCs in China, selected from the 126 identified in "the Plan", after accounting for administrative mergers and data availability. The 2020 prefecture-level administrative divisions serve as the spatial reference. Following "the Plan," the sample RBCs are categorized by developmental stage (growing, mature, declining, regenerative), by dominant resource (metal, non-metal, forestry, coal, oil & gas), and by geographic region (eastern, central, western, northeastern). Their spatial distribution and typology are presented in Fig. 2.

### Source of data

The research period of 2005–2020 was determined based on the availability, continuity, and completeness of the data. Administrative vector boundaries for the 110 prefecture-level RBCs (based on the 2020 division standards) were acquired from the Resource and Environment Science and Data Center of the Chinese Academy of Sciences (<http://www.resdc.cn/DOI>). Socio-economic data were compiled from a range of official publications, including the China City Statistical Yearbook, the China Urban Construction Statistical Yearbook, relevant provincial and municipal statistical yearbooks, and Statistical Bulletins of National Economic and Social Development spanning 2005 to 2021.

Gaps in the socio-economic data were filled employing a linear interpolation approach. The panel data utilized in this study exhibit a high degree of completeness, with a missing value proportion of less than 2%. These missing values are sporadically distributed only across socio-economic indicators in individual years. To



**Fig.2.** Distribution and types of 110 RBCs in China.

address such random and limited missing data, the linear interpolation method was employed for imputation. This approach, grounded in the assumption of smooth variation in variables between adjacent years, is a standard practice for handling missing data in time series analysis. It effectively minimizes the impact on the overall data distribution and composite evaluation results while preserving sample size and data continuity. It should be noted that alternative methods would have been necessary in the case of systematic missing data (e.g., the prolonged absence of specific data for a certain category of cities); however, no such situation was encountered in this research.

For land use analysis, the study relied on the authoritative Annual China Land Cover Dataset<sup>37</sup>, which offers high accuracy and temporal consistency and has been extensively cited in scholarly work<sup>38,39</sup>. This dataset was reclassified into a six-category schema for this study: construction land, cultivated land, forest land, grassland, water and wetland, and unused land.

## Methods of research

### *Comprehensive measurement model of TSDPL*

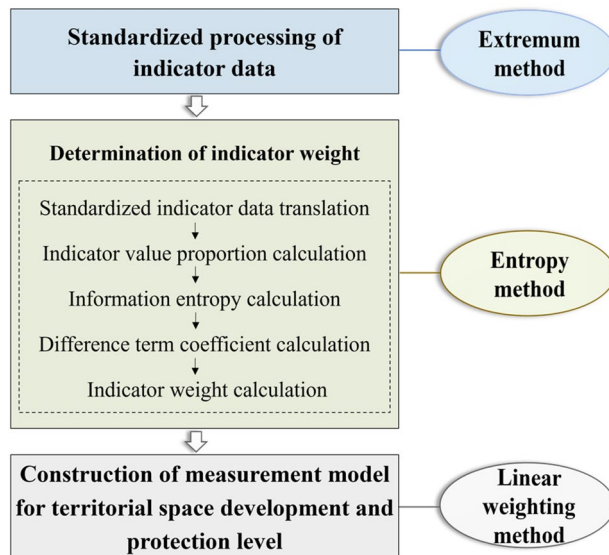
The TSDPL measurement was conducted using a comprehensive model built in three stages. The initial data were first standardized to eliminate dimensionality. Subsequently, individual indicator weights were assigned<sup>40</sup>. These were then integrated into the final model to compute the comprehensive TSDPL score for each city. A detailed schematic of the model construction process is presented in Fig. 3.

- (1) The data are normalized using the extremum method. Suppose that there are  $h$  years,  $m$  cities, and  $n$  indicators, then  $x_{\theta ij}$  is the original value of the  $j$ -th indicator of city  $i$  in year  $\theta$ . In this study,  $h = 16$ ,  $m = 110$ , and  $n = 22$ . The calculation formula of data standardization is as follows:

$$\text{Positive indicators} : x'_{\theta ij} = \frac{x_{\theta ij} - x_{j \min}}{x_{j \max} - x_{j \min}} \quad (1)$$

$$\text{Negative indicator} : x'_{\theta ij} = \frac{x_{j \max} - x_{\theta ij}}{x_{j \max} - x_{j \min}} \quad (2)$$

In the formula,  $x'_{\theta ij}$  is the value of the original indicator data after standardization, and the value is between 0–1;  $x_{j \max}$  and  $x_{j \min}$  are the maximum and minimum values of the  $j$ -th indicator, respectively.



**Fig.3.** Steps for constructing the comprehensive measurement model for TSDPL.

(2) Indicator weighting using the entropy method.

As an objective weighting method based on data structure, the entropy method is fully based on the discrete nature of the data itself, which overcomes the subjectivity of index weighting, and the obtained index weight has high credibility, which effectively improves the scientific nature of multi-index evaluation system, so it has been widely used<sup>40</sup>.

(1) Data translation. The calculation formula is as follows:

$$X_{\theta ij} = x'_{\theta ij} + 0.0001 \tag{3}$$

In the formula,  $X_{\theta ij}$  is the value of the standardized indicator data after translation,  $X_{\theta ij} > 0$ .

(2) Calculate the proportion  $p_{\theta ij}$  of the indicator value of city  $i$  in the  $\theta$ -th year under the  $j$ -th indicator, and the formula is:

$$p_{\theta ij} = \frac{X_{\theta ij}}{\sum_{\theta=1}^h \sum_{i=1}^m X_{\theta ij}} \tag{4}$$

(3) Calculate the information entropy  $E_j$  of the  $j$ -th indicator as follows:

$$E_j = -\frac{1}{\ln(hm)} \times \sum_{\theta=1}^h \sum_{i=1}^m p_{\theta ij} \ln(p_{\theta ij}) \tag{5}$$

(4) Calculate the difference coefficient  $G_j$  of the  $j$ -th indicator, and the formula is:

$$G_j = 1 - E_j \tag{6}$$

(5) Calculate the weight  $w_j$  of the  $j$ -th indicator as follows:

$$w_j = \frac{G_j}{\sum_{j=1}^n G_j}, \quad (0 \leq w_j \leq 1); \quad \sum_{j=1}^n w_j = 1 \tag{7}$$

(3) Measurement model construction using the linear weighting method:

$$S_{\theta i} = \sum_{j=1}^n (w_j \times X_{\theta ij}) \quad (8)$$

In the formula,  $S_{\theta i}$  is the comprehensive indicator value of TSDPL of city  $i$  in the  $\theta$ -th year.

This study employs the entropy weight method for objective weighting to minimize subjective bias. It should be noted that the composite index results are somewhat dependent on the choice of weighting method. Although the entropy weight method determines weights based on the dispersion of the data, offering relatively good robustness, the use of alternative weighting approaches (such as the analytic hierarchy process or expert scoring method) could lead to differences in weight allocation. This, in turn, might affect the absolute scores and relative rankings of TSDPL for individual cities. Future research could further test the robustness of the conclusions by comparing different weighting methods or conducting sensitivity analyses.

#### *Center of gravity transfer model and standard deviation ellipse method.*

The center of gravity transfer model effectively delineates the spatiotemporal migration patterns of geographical elements<sup>41</sup>, while the standard deviation ellipse method captures their directional distribution and expansion<sup>42</sup>. Used in combination, these two methods provide a comprehensive framework for analyzing the spatiotemporal evolution characteristics and migratory trends of geographical elements<sup>43–45</sup>.

#### *Exploratory spatial data analysis.*

Exploratory spatial data analysis is categorized by scale into global and local spatial autocorrelation. The former assesses overall spatial dependency, while the latter evaluates correlations between individual units and their neighbors<sup>46</sup>. We apply global Moran's  $I$ <sup>47</sup> to test for general spatial clustering of TSDPL, complemented by local Moran's  $I$ <sup>48</sup> to pinpoint local agglomeration patterns. Additionally, the Getis-Ord  $G_i^*$  index<sup>49</sup> is used to identify statistically significant hot spots and cold spots of TSDPL, revealing spatial associations between each city and its vicinity.

#### *Kernel density estimation.*

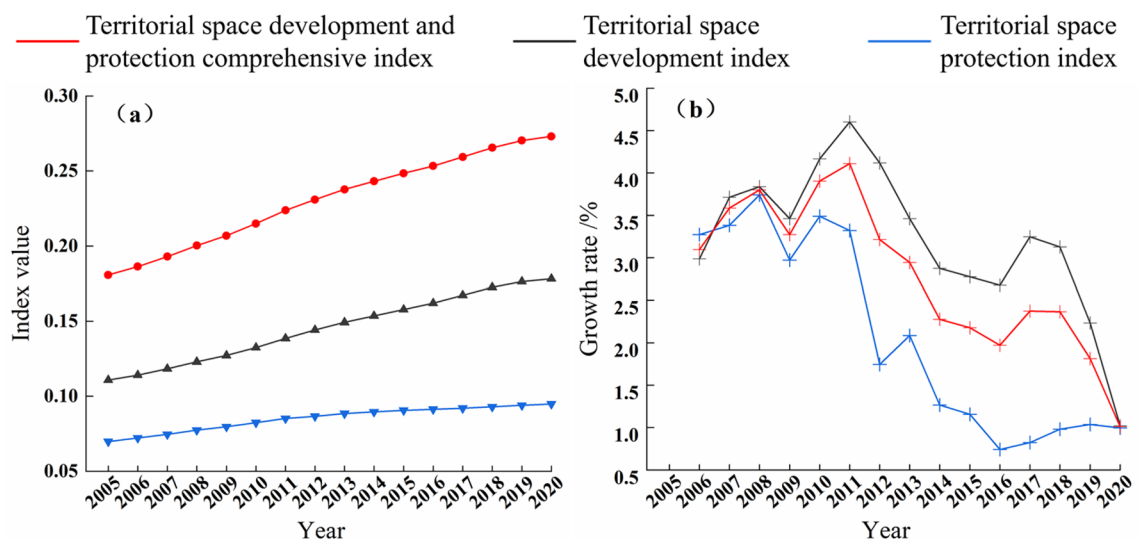
The kernel density estimation method, which models the dynamic evolution and staged distribution of a variable through a continuous density curve<sup>50</sup>, is implemented using Stata 17.0. This approach allows for an analysis of the distribution dynamics and thereby reveals the evolution of the absolute differences in TSDPL across RBCs from 2005 to 2020<sup>51–53</sup>.

## Temporal evolution of TSDPL in China's RBCs

### Overall cities

According to the measurement model of TSDPL, the comprehensive index, development index, protection index and the growth rate of each index of 110 cities from 2005 to 2020 are calculated (Fig. 4).

During the study period, the comprehensive, development, and protection indices all exhibited continuous growth (Fig. 4a). The growth trend of the development index closely aligned with that of the comprehensive index, whereas the protection index rose more gradually. Notably, the protection index remained significantly lower than the development index throughout, indicating a persistent structural imbalance where territorial space development consistently outpaced protection efforts in these cities.



**Fig. 4.** Temporal variation of the TSDP index value and its growth rate of the overall RBCs.

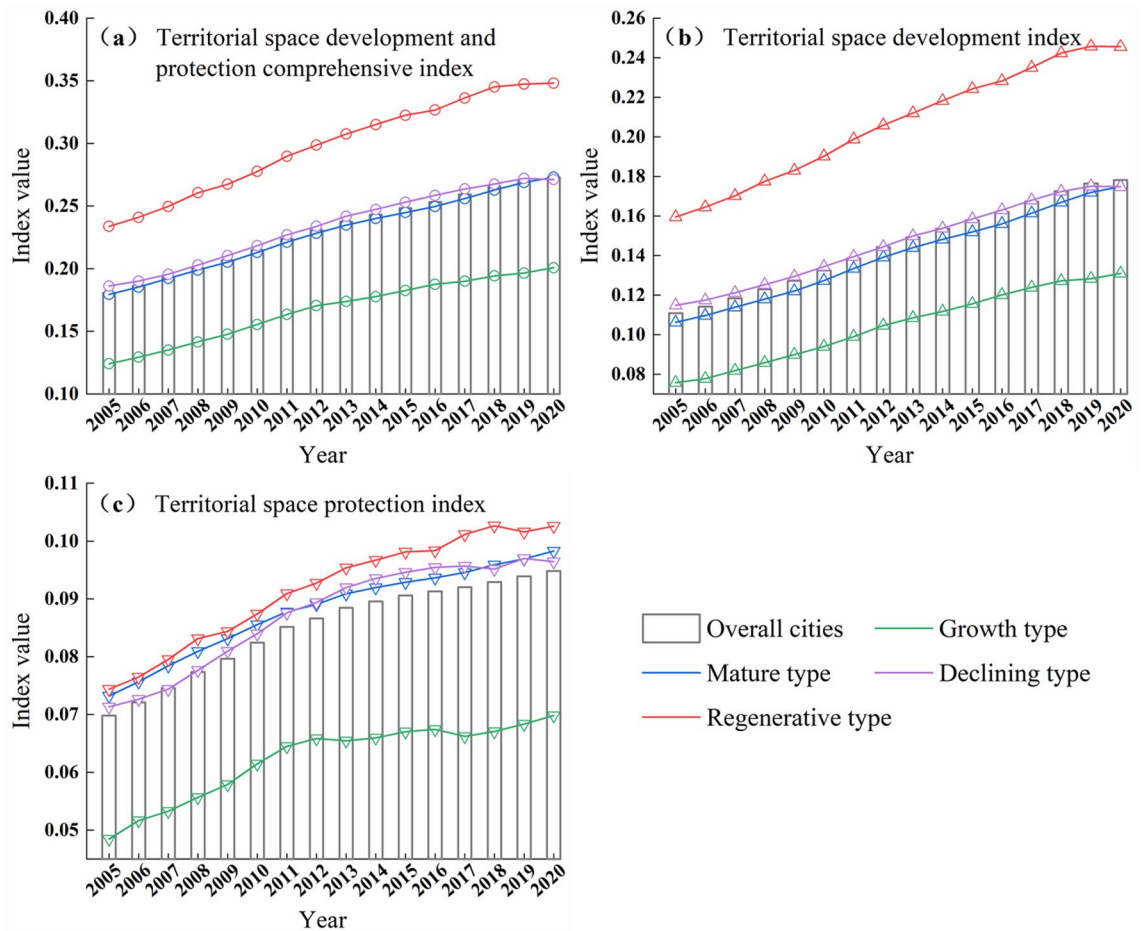


Fig.5. Temporal evolution characteristics of TSDP index of cities in different development stages.

Type of cities	Average annual index value			Average annual growth rate of index (%)		
	Comprehensive index	Development index	Protection index	Comprehensive index	Development index	Protection index
Growth type	0.167	0.105	0.062	3.260	3.727	2.467
Mature type	0.228	0.140	0.088	2.838	3.375	1.983
Declining type	0.233	0.146	0.087	2.539	2.838	2.030
Regenerative type	0.298	0.206	0.092	2.690	2.922	2.166
The overall	0.230	0.145	0.085	2.791	3.217	2.061

Table 2. Summary of TSDP index value of cities in different development stages.

The growth rates of all three indices displayed fluctuating declines over time, with the development and comprehensive indices showing particularly synchronized movements (Fig. 4b). Specifically, from 2006 to 2011, the growth rates of all indices fluctuated upward. Between 2011 and 2016, they entered a phase of fluctuating decline. From 2016 to 2020, the growth rate of the protection index gradually recovered, while that of the comprehensive and development indices experienced a sharp drop, reaching its lowest point in 2020. This pronounced decline is likely associated with the widespread disruption caused by the COVID-19 pandemic, which severely impacted economic and development activities. Furthermore, this sharp contraction may also expose the underlying vulnerability of growth models in some RBCs that remain overly reliant on traditional development-intensive sectors.

### Cities in four stages of development

Analysis of the annual averages revealed a clear ranking in the comprehensive index across city types: regenerative (0.298) > declining (0.233) > mature (0.228) > growth (0.167) (Fig. 5a). This ranking reflects the cumulative outcome of long-term transition efforts. Conversely, the average annual growth rate of the comprehensive index was highest in growth type cities (3.260%) and lowest in declining type cities (2.539%), before recovering in the regenerative stage (Table 2). A similar pattern was observed for the development index (Fig. 5b), while

the protection index was consistently lower across all types, with values ranging from 0.062 (growth) to 0.092 (regenerative) (Fig. 5c). This persistent gap underscores a systemic lag in ecological and conservation efforts relative to development, indicating that enhancing protection remains a critical challenge throughout the urban development cycle, even for advanced regenerative type cities.

The TSDPL across different urban development stages (Fig. 6) demonstrates the following characteristics:

- (1) Growth type cities display the lowest absolute TSDPL but the highest growth rate, consistent with their initial stage of resource-driven economic expansion.
- (2) Mature type cities achieve a relatively high TSDPL, benefiting from established socio-economic structures and efficient resource exploitation systems.
- (3) Declining type cities maintain a TSDPL comparable to mature cities, aided by residual economic infrastructure and mature extraction technologies, yet exhibit the lowest growth rate due to resource exhaustion and industrial decline.
- (4) Regenerative type cities reach the highest TSDPL, as their economic development shifts toward a more intensive and sustainable pathway through industrial optimization and reduced resource reliance.

### Cities with five dominant resource types

The temporal evolution of TSDPL in cities categorized by dominant resource type is shown in Fig. 7. The annual average comprehensive index ranked as follows: non-metallic-based (0.267), oil and gas-based (0.241), coal-based (0.238), metal-based (0.212), and forestry-based (0.182) (Table 3). In terms of growth rate, the comprehensive index increased most rapidly in coal-based cities (2.882%), followed by non-metallic-based (2.805%), metal-based (2.787%), oil and gas-based (2.786%), and forestry-based cities (1.781%). Non-metallic-based cities thus exhibited both the highest comprehensive index and a consistently high growth rate, whereas forestry-based cities displayed the opposite pattern.

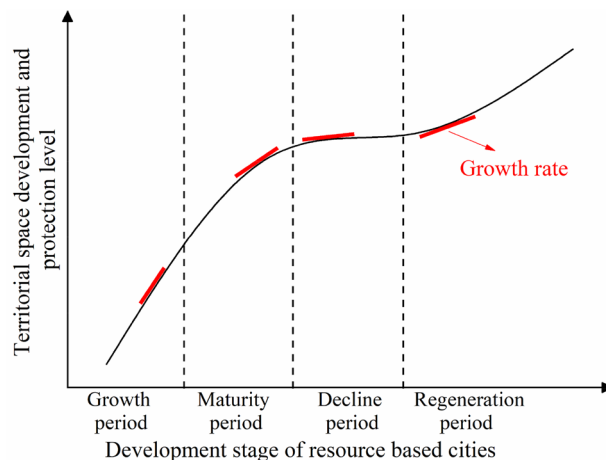
The development index was highest in coal-based cities (0.163), followed closely by non-metallic-based and oil and gas-based cities (both 0.161), then metal-based (0.116), and forestry-based cities (0.082). The average annual growth rate of the development index was highest in metal-based cities and lowest in oil and gas-based cities.

Regarding the protection index, non-metallic-based cities showed steady growth and consistently outperformed other resource types after 2013. In contrast, coal-based and oil and gas-based cities maintained relatively low protection indices, though their average annual growth rates were comparatively high. Forestry-based cities recorded a relatively high protection index, and were the only category in which the average annual protection index (0.100) exceeded the development index (0.082).

Analysis of TSDPL characteristics across cities with different dominant resource types revealed distinct patterns (Fig. 8). With the exception of forestry-based cities, all other resource categories consistently exhibited a developmental pattern characterized by higher development than protection levels, underscoring a pervasive tendency to prioritize economic and spatial expansion over ecological stewardship.

Coal-based cities demonstrated the most pronounced disparity, recording the highest development index concurrently with the lowest protection index. Oil and gas-based cities displayed a highly similar profile, suggesting that energy-intensive resource types face comparable challenges in balancing exploitation with conservation, likely due to similar industrial structures and environmental externalities. Metal-based cities showed moderate values in both development and protection indices, resulting in an overall low TSDPL.

Forestry-based cities presented a unique configuration, exhibiting the lowest development index alongside a relatively high protection index. This inverse relationship highlights their primary role as ecological buffers, where conservation is prioritized but economic diversification remains limited, resulting in constrained overall performance under conventional development metrics. In contrast, non-metallic-based cities achieved balanced development, maintaining relatively high values in both indices, which corresponded to the highest overall



**Fig. 6.** Characteristics of TSDPL of cities in different development stages.

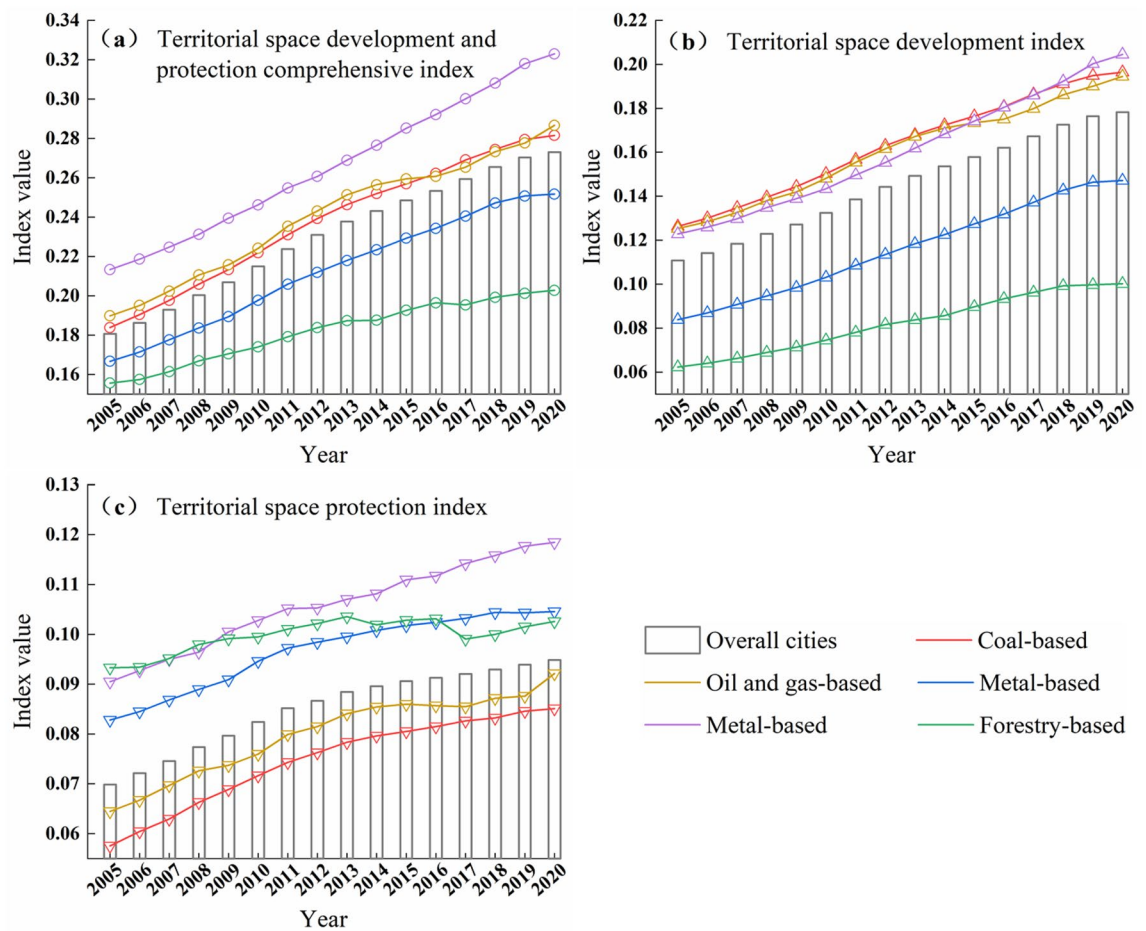


Fig.7. Temporal variation characteristics of TSDP index of cities with different resource types.

Type of cities	Average annual index value			Average annual growth rate of index (%)		
	Comprehensive index	Development index	Protection index	Comprehensive index	Development index	Protection index
Coal-based	0.238	0.163	0.075	2.882	2.989	2.641
Oil and gas-based	0.241	0.161	0.080	2.786	2.973	2.408
Metal-based	0.212	0.116	0.097	2.787	3.821	1.567
Non-metallic-based	0.267	0.161	0.106	2.805	3.460	1.812
Forestry-based	0.182	0.082	0.100	1.781	3.219	0.634
The overall	0.230	0.145	0.085	2.791	3.217	2.061

Table 3. Summary of TSDP index value of cities with different resource types.

TSDPL among all resource types. This suggests that cities relying on resources such as limestone or clay benefit from greater industrial flexibility, lower environmental disruption, and stronger alignment with construction and manufacturing value chains, enabling more synergistic development-protection outcomes.

### Cities in four distribution regions

The comprehensive index across the four distribution regions exhibited a consistent upward trend from 2005 to 2020 (Fig. 9). From 2005 to 2013, all regions experienced steady growth in the comprehensive index. After 2013, a divergence emerged: the comprehensive index in the northeastern region began a gradual decline, while the other three regions maintained their upward trajectory. The overall ranking of the comprehensive index, in descending order, was eastern, central, northeastern, and western regions.

The growth rate of the comprehensive index also varied regionally, with the western region showing the highest average annual growth (3.212%), followed by the central (2.941%), eastern (2.937%), and northeastern regions (1.583%) (Table 4).

The development index in all four regions followed a trend similar to that of the comprehensive index (Fig. 9b). In contrast, the protection index displayed greater fluctuation (Fig. 9c). From 2005 to 2013, the

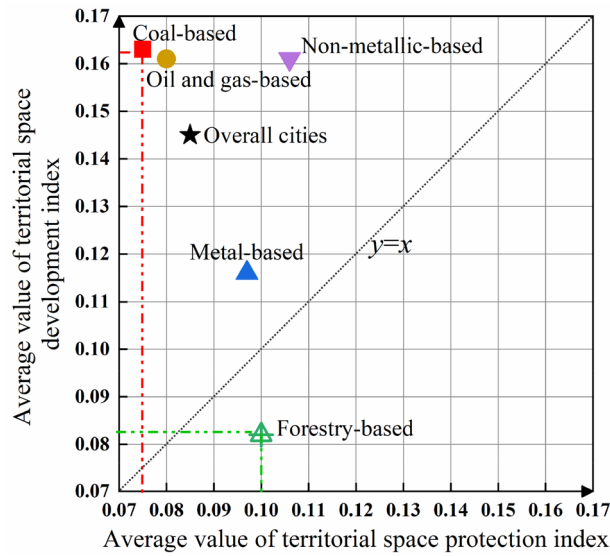


Fig.8. Characteristics of TSDPL of cities with different resource types.

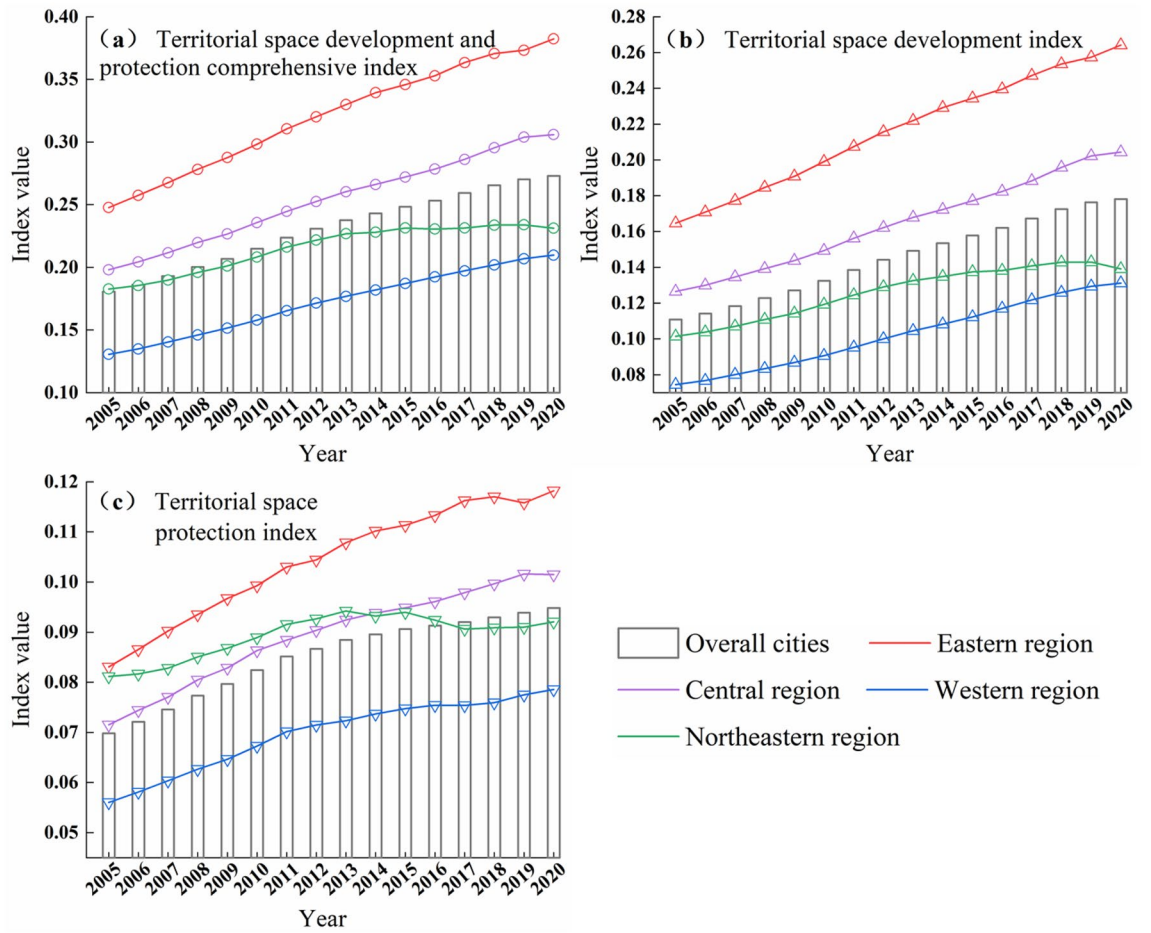


Fig.9. Temporal variation characteristics of TSDP index of cities in different regions.

Type of cities	Average annual index value			Average annual growth rate of index (%)		
	Comprehensive index	Development index	Protection index	Comprehensive index	Development index	Protection index
Eastern region	0.320	0.216	0.104	2.937	3.202	2.382
Central region	0.254	0.165	0.089	2.941	3.250	2.361
Western region	0.172	0.102	0.070	3.212	3.845	2.278
Northeastern region	0.215	0.126	0.089	1.583	2.126	0.844
The overall	0.230	0.145	0.085	2.791	3.217	2.061

**Table 4.** Summary of TSDP index value of cities in different regions.

northeastern region maintained a relatively high protection index, which began to decline after 2013. The other three regions demonstrated steady growth in their protection indices throughout the study period. The eastern region consistently exhibited a pattern of "high development and high protection," while the western region showed the opposite. The northeastern region recorded the lowest average annual growth rates for both the development and protection indices.

The observed regional disparities in TSDPL can be attributed to several underlying factors. The higher comprehensive index in the eastern and central regions reflects their established role as the core of China's economic development, resulting in a higher baseline at the beginning of the study period. The subsequent decline in the northeastern region may be linked to its unreasonable industrial structure and the neglect of environmental quality in urban development.

The rapid growth in the western region appears to be influenced by the Western China Development Strategy, which has promoted continuous regional advancement. Conversely, the northeastern region's slow improvement coincides with increasingly prominent structural problems, including a singular industrial structure, population loss, and urban shrinkage.

From 2005 to 2020, the TSDPL exhibited a distinct regional hierarchy, descending from the eastern, to the central, northeastern, and western regions, a pattern closely aligned with China's prevailing economic geography.

As the most economically advanced region, the eastern region consistently recorded high values across all three indices—comprehensive, development, and protection. The central region experienced rapid development and correspondingly high TSDPL following the implementation of the "Rise of Central China" policy in 2004. In contrast, the northeastern region, with its heavy reliance on resource extraction and imbalanced industrial structure, demonstrated a relatively low development index. The western region, characterized by a lower level of socio-economic development, displayed a comparatively limited capacity for TSDP, ultimately leading to its lowest regional TSDPL.

## Spatial evolution characteristics of TSDPL in RBCs in China

### Spatial pattern characteristics

Based on the calculated comprehensive indices of TSDP, a spatial distribution map of TSDPL was generated (Fig. 10). The Jenks natural breaks classification method was employed to categorize TSDPL into five distinct levels: low (0.0590–0.1530), relatively low (0.1531–0.2110), medium (0.2111–0.2820), relatively high (0.2821–0.3750), and high (0.3751–0.5530).

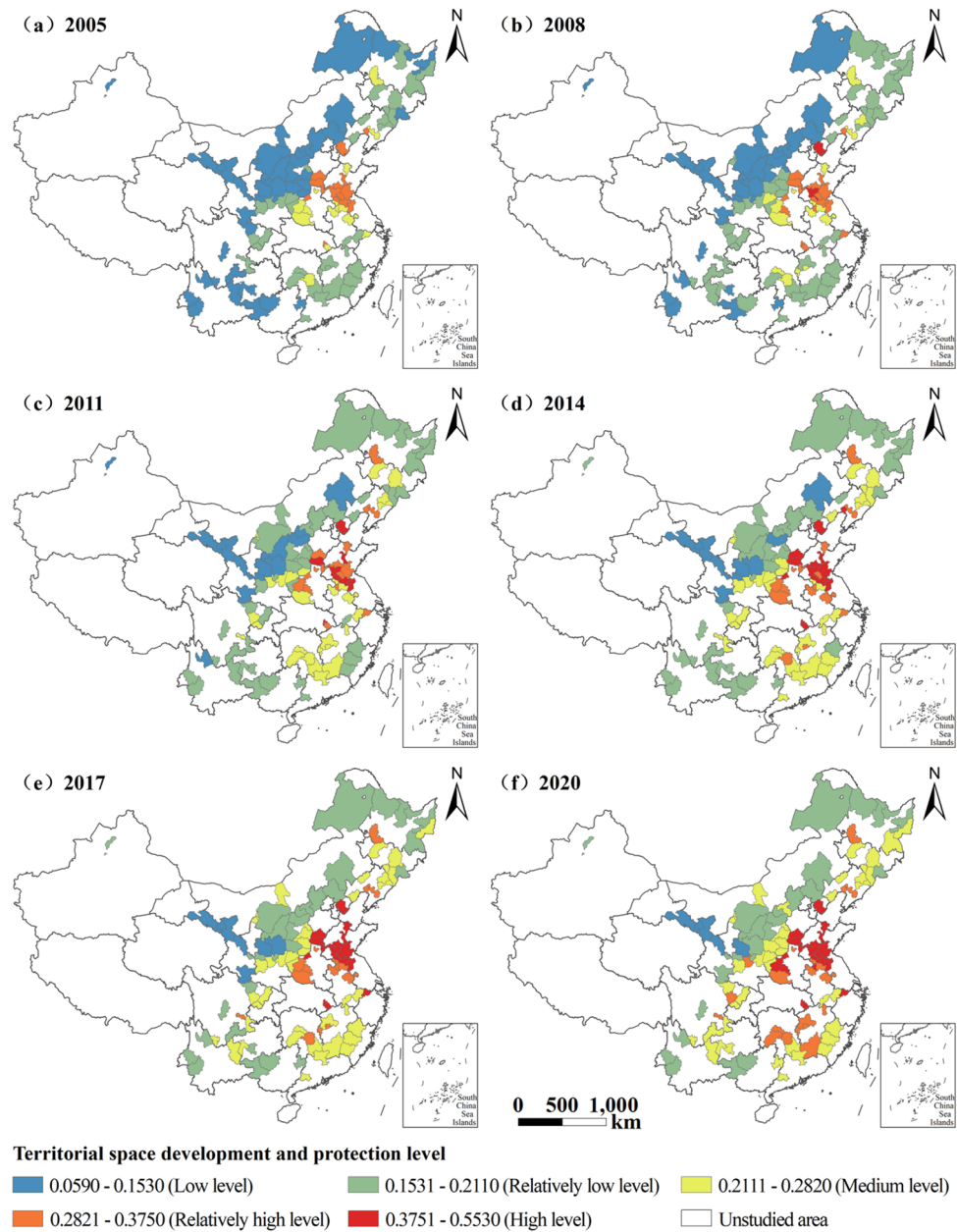
The TSDPL generally exhibits a distinct spatial pattern characterized by higher values in the eastern and southern regions and lower values in the western and northern parts of China. Cities with high and relatively high TSDPL are predominantly concentrated in the eastern provinces of Hebei, Shandong, and Jiangsu, as well as Henan in the central region. In contrast, cities with low and relatively low TSDPL are mainly distributed in Gansu, Shaanxi, and the Inner Mongolia Autonomous Region in the west, Heilongjiang in the northeast, and Shanxi in the central region.

Among these, Shandong Province contains the largest number of cities with high TSDPL, whereas Gansu Province has the highest number of cities with low TSDPL. This disparity can be attributed to regional developmental pathways. In Shandong, most RBCs are classified as mature or regenerative. Supported by provincial strategies such as "Replacing Old Growth Drivers with New Ones" and "Ecological Shandong," the region has progressively transitioned toward an intensive and sustainable development model. Conversely, RBCs in Gansu remain heavily reliant on natural resources, with economic development dominated by heavy industry. This has resulted in a monotonous industrial structure and limited environmental benefits, constraining overall TSDPL improvement.

### Characteristics of spatial distribution direction

ArcGIS 10.2 software was utilized to derive the standard deviation ellipse parameters of TSDPL. Based on these parameters, the movement direction of the spatial center of gravity, the shape index (defined as the ratio of the short semi-axis to the long semi-axis), and the migration distance were calculated (Table 5). This analysis further revealed the spatiotemporal evolution pattern characterizing the spatial diffusion of TSDPL (Fig. 11).

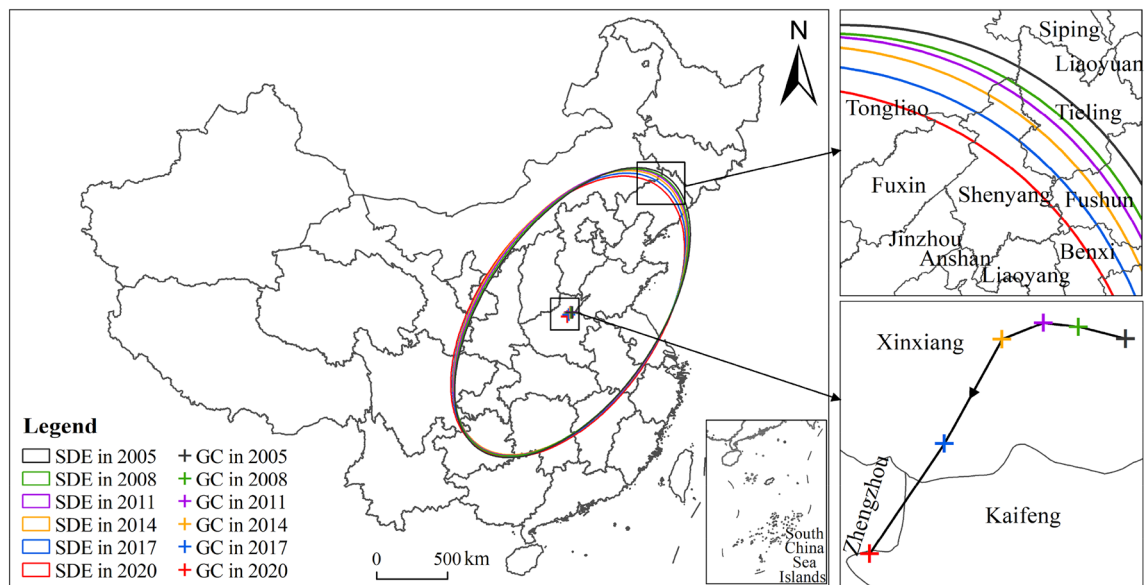
- (1) Changes in the gravity center of spatial distribution.



**Fig.10.** The spatial distribution of TSDPL of RBCs from 2005 to 2020.

Year	Center of gravity migration			Standard deviation ellipse				
	Longitude of gravity center (°E)	Latitude of gravity center (°N)	Migration distance (km)	Standard deviation of x (km)	Standard deviation of y (km)	Elliptical abundance	Ellipse area (10,000 square kilometers)	Azimuth angle (°)
2005	114.558	35.055		619.294	1192.784	0.519	232.044	33.312
2008	114.491	35.074	6.442	624.087	1177.475	0.530	230.839	33.195
2011	114.440	35.083	4.672	631.629	1170.336	0.540	232.213	33.078
2014	114.376	35.068	5.947	636.320	1160.019	0.549	231.876	33.067
2017	114.277	34.950	16.041	637.862	1153.737	0.553	231.179	33.095
2020	114.152	34.826	17.939	646.333	1143.978	0.565	232.268	33.231

**Table 5.** The parameters of center of gravity migration and standard deviation ellipse of TSDPL.



**Fig. 11.** The standard deviation ellipse (SDE) and gravity center (GC) migration path of TSDPL from 2005 to 2020.

The spatial center of gravity of TSDPL was consistently located within Henan Province throughout the study period. Its trajectory shifted from a northwesterly direction (2005–2011) to a southwesterly direction (2011–2020), with a total displacement of 51.041 km, indicating an overall movement toward the southwest.

The migration speed in the northwest direction gradually decreased, from 2.147 km/year during 2005–2008 to 1.557 km/year during 2008–2011. In contrast, the speed of southwestward movement increased consistently, from 1.982 km/year (2011–2014) to 5.347 km/year (2014–2017) and further to 5.980 km/year (2017–2020). Overall, the migration velocity of TSDPL exhibited a trend of initial decrease followed by sustained acceleration.

The observed shift in the spatial center of gravity may be attributed to regional development strategies. Influenced by national initiatives such as the Rise of Central China and the Western China Development Strategy, the gradual transfer of capital and technological resources to central and western regions has stimulated economic growth, thereby driving the southwestward movement of the TSDPL gravity center.

## (2) Changes in the spatial distribution range and direction.

The standard deviation ellipse of TSDPL exhibited an area fluctuating around 2.32 million square kilometers, with an azimuth angle of approximately 33°, indicating a persistent "northeast–southwest" orientation in the spatial pattern. Overall, the spatial distribution of TSDPL was predominantly aligned along the north–south direction and demonstrated an expanding trend over the study period. The increasing ellipticity of the standard deviation ellipse suggests a gradual weakening in the directionality of the TSDPL spatial distribution.

## Spatial correlation feature

### (1) Global spatial autocorrelation

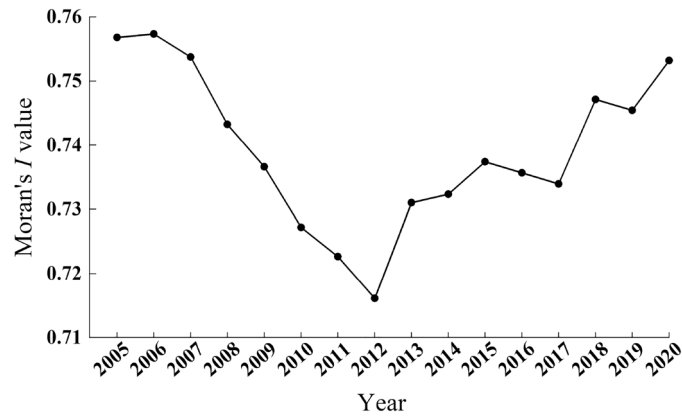
During the study period, the global Moran's I index for TSDPL remained positive, indicating a statistically significant positive spatial autocorrelation in its distribution (Fig. 12). From 2005 to 2012, the index exhibited a declining trend, reflecting a gradual weakening in the degree of spatial agglomeration of TSDPL. In contrast, from 2012 to 2020, the global Moran's I index showed a fluctuating upward trend, suggesting a re-intensification of spatial clustering during this period.

### (2) Local spatial autocorrelation.

#### 1. Analysis of spatial agglomeration characteristics.

Based on the local Moran's I index and TSDPL values, local spatial autocorrelation was categorized into three types:

- ① High-High (HH) type: Cities with high TSDPL surrounded by neighbors with similarly high values.
- ② Low-Low (LL) type: Cities with low TSDPL surrounded by neighbors with similarly low values.



**Fig. 12.** The evolution characteristics of the global Moran's I index of TSDPL from 2005 to 2020.

③ High-Low (HL) type: Cities with high TSDPL surrounded by neighbors with low values.

As shown in Fig. 13, HH-type cities were predominantly concentrated in Shandong Province in the eastern region, forming a contiguous spatial cluster spanning Shandong, Jiangsu, Anhui, Hebei, and Henan, with scattered occurrences in Hubei. LL-type cities were mainly distributed in Gansu and Yulin (Shaanxi) in the western region, as well as Xinzhou (Shanxi) in the central region. The only HL-type city identified was Tangshan in Hebei Province.

Throughout the study period, the spatial extent of HH-type cities remained relatively stable, while that of LL-type cities gradually decreased. The HL-type agglomeration appeared only in certain years and was consistently localized in Tangshan, indicating a solidified pattern in the spatial agglomeration characteristics of TSDPL.

## 2. Spatial cold and hot spot analysis.

The spatial distribution of hot spots and cold spots of TSDPL exhibits marked spatial heterogeneity (Fig. 14), demonstrating a distinct east-to-west decreasing gradient. This pattern reinforces the core-periphery structure of China's regional development, where eastern coastal provinces, with their early reform advantages and diversified economies, have been able to establish a more sustainable balance between development and protection.

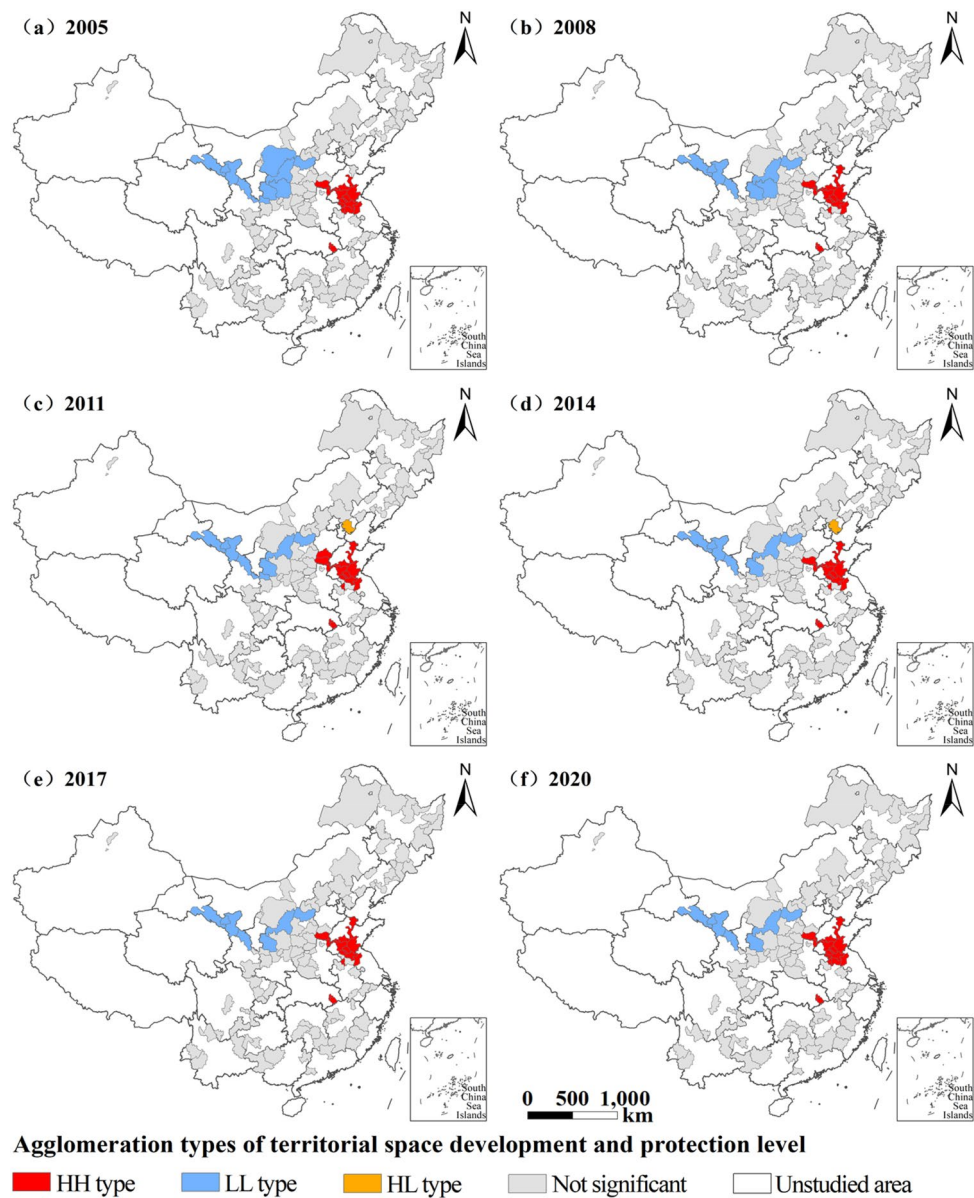
Hot spots form a contiguous cluster in Shandong and Jiangsu in the eastern region, with scattered occurrences in Panjin and Anshan (northeastern region), as well as in Luoyang (Henan), Ezhou, and Huangshi (Hubei) in the central region. The agglomeration in Shandong and Jiangsu suggests the presence of positive spatial spillovers and regional synergy, driven by integrated infrastructure, policy coordination, and knowledge diffusion within these economic zones. The isolated hot spots in the northeast and central regions represent local breakthroughs where specific cities have outperformed their regional context through unique industrial restructuring or strong environmental governance. Cold spots are continuously distributed across Gansu, Inner Mongolia, and Shaanxi in the western region, and extend into Shanxi in the central region. This contiguous belt of low TSDPL highlights the persistent challenges faced by resource-dependent and ecologically fragile regions, where the legacy of heavy industry, geographical constraints, and weaker institutional capacity collectively hinder synergistic development.

Hot spots display a "locked" spatial evolutionary pattern, with the number of cities remaining constant at 19 throughout the study period. In contrast, cold spot areas underwent slight spatial changes. Specifically, Ordos, Baotou, Shuozhou, Datong, and Xianyang transitioned from cold spots in 2005 to non-significant areas by 2020, whereas Heihe and Yichun in Heilongjiang shifted from non-significant to cold spots. Overall, the number of cities classified as cold spots decreased from 15 to 12, revealing a "shrinking" spatial characteristic. The reduction in cold spots is an encouraging sign, potentially reflecting the gradual positive impact of national regional strategies like Western Development. However, the emergence of new cold spots in Heilongjiang is concerning and may signal the deepening of transition difficulties in some northeastern regions, possibly due to resource depletion, economic stagnation, or outmigration exacerbating the development-protection imbalance. This dynamic underscores that while broad regional trends are improving, localized regression remains a risk, necessitating continued focused policy attention.

## Evolution trend of TSDPL in China's RBCs

Kernel density estimation was performed using Stata 17.0 to analyze the distribution dynamics and evolutionary trends of TSDPL for the overall sample of cities, as well as across different development stages, dominant resource types, and geographical regions (see Fig. 15, 16, 17, 18).

(1) Kernel density analysis reveals distinct evolutionary patterns in TSDPL distribution. The kernel density curves for both the aggregate sample and all city subtypes exhibited a consistent rightward shift in peak position, indicating sustained improvement in TSDPL values across all categories. For the overall sample,

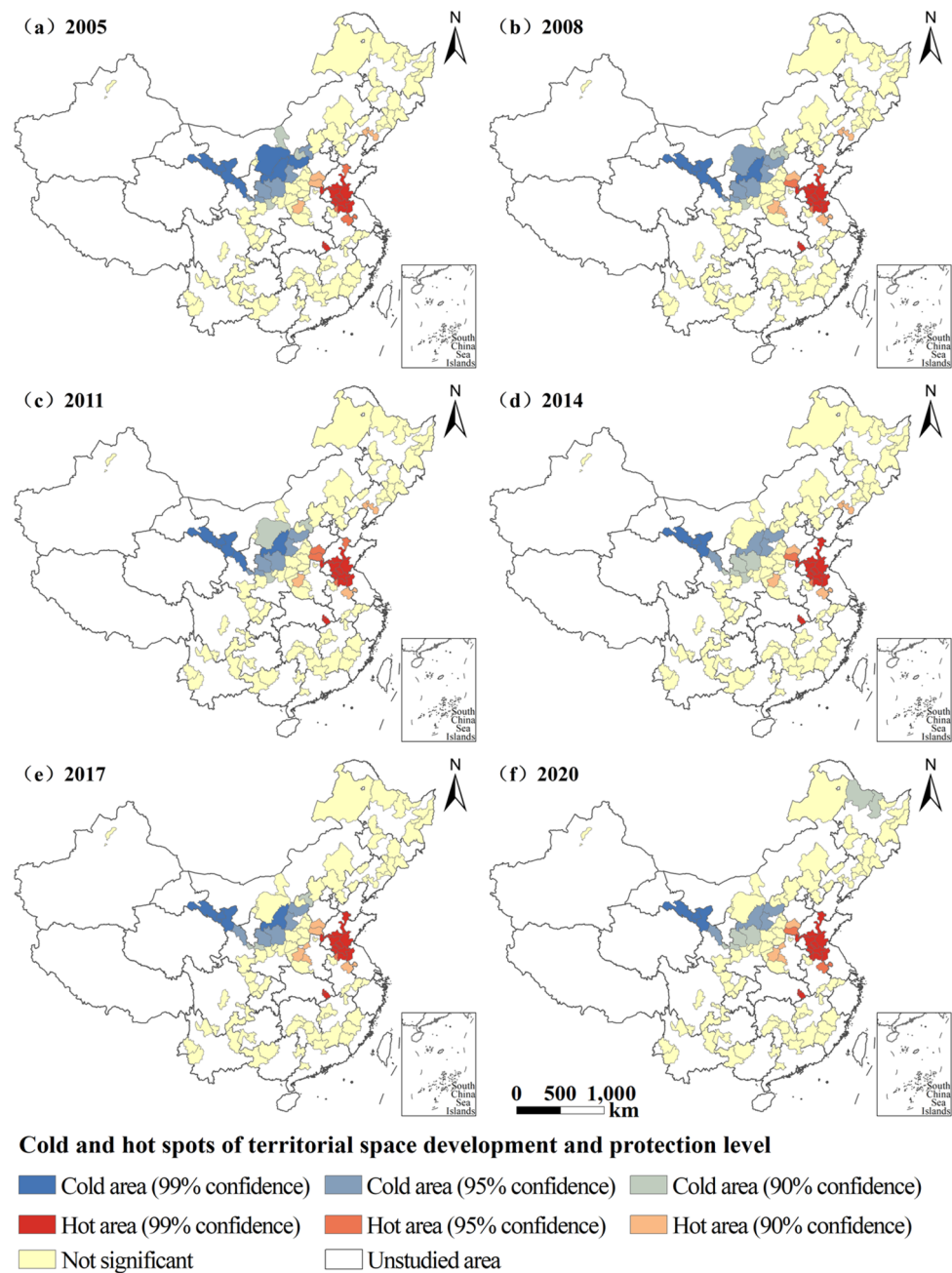


**Fig.13.** The spatial distribution of agglomeration types of TSDPL from 2005 to 2020.

the distribution demonstrated decreasing peak height alongside increasing distribution width, reflecting a widening disparity in TSDPL among cities. However, the evolution of internal disparities varied substantially across city types. Growth type cities showed a narrowing internal gap, while the other three development types exhibited widening disparities. Regional analysis indicated expanding TSDPL gaps within the eastern, central, and western regions. The northeastern region followed a distinct trajectory, with disparities gradually widening until 2014, followed by a phase of subsequent convergence.

(2) Analysis of the kernel density curves further reveals distinct polarization dynamics in TSDPL distribution. For the overall sample, the curve features a primary peak and a distinct secondary peak to the right, with the distance between them narrowing over time. This pattern indicates the presence of polarization in TSDPL across cities, and that this divergence is gradually intensifying. Variations in polarization are evident across city categories:

- ① By development stage, polarization among growth type cities gradually faded, though a trend toward multi-polarization emerged. Multi-polarization appeared only slightly in mature type cities, gradually diminished in declining type cities, and began to develop in regenerative type cities.
- ② By resource type, coal-based cities exhibited mild multi-polarization. In contrast, polarization weakened among oil and gas-based, metal-based, and non-metallic-based cities, and decreased substantially among forestry-based cities.



**Fig.14.** The spatial hot and cold spot distribution of TSDPL from 2005 to 2020.

- ③ By geographical region, polarization weakened markedly in the eastern region. Multi-polarization gradually emerged—though not prominently—in the central region, while it weakened in the western region. In the northeastern region, polarization generally diminished but showed signs of re-intensification in 2020.
- (3) The distribution curve's tail evolution provides additional insights into TSDPL disparities. For the overall sample, both left and right tails exhibited a consistent rightward shift, with the right tail extending further than the left. This pattern signifies improvement in both high-value and low-value areas, alongside a widening absolute gap in TSDPL between cities. Distinct evolutionary patterns emerged across city categories:
- ① By development stage, growth, mature, and declining type cities all showed improvement in both high-value and low-value areas, accompanied by a decreasing proportion of cities in low-value zones.
- ② By resource type, all five categories demonstrated improvement in both high and low-value areas, with coal-based cities additionally showing an increasing proportion of high-value cities.

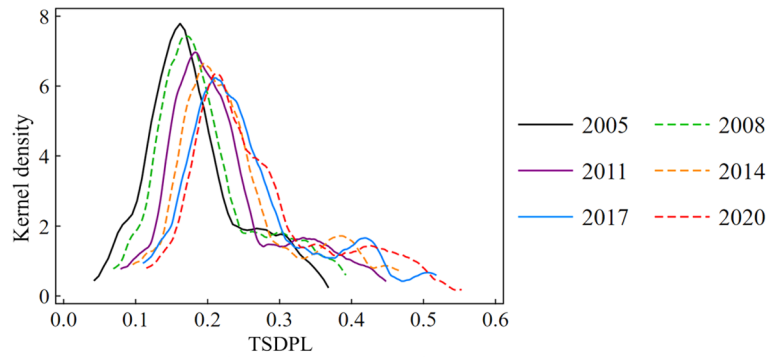


Fig.15. The kernel density estimation of TSDP index of the overall RBCs.

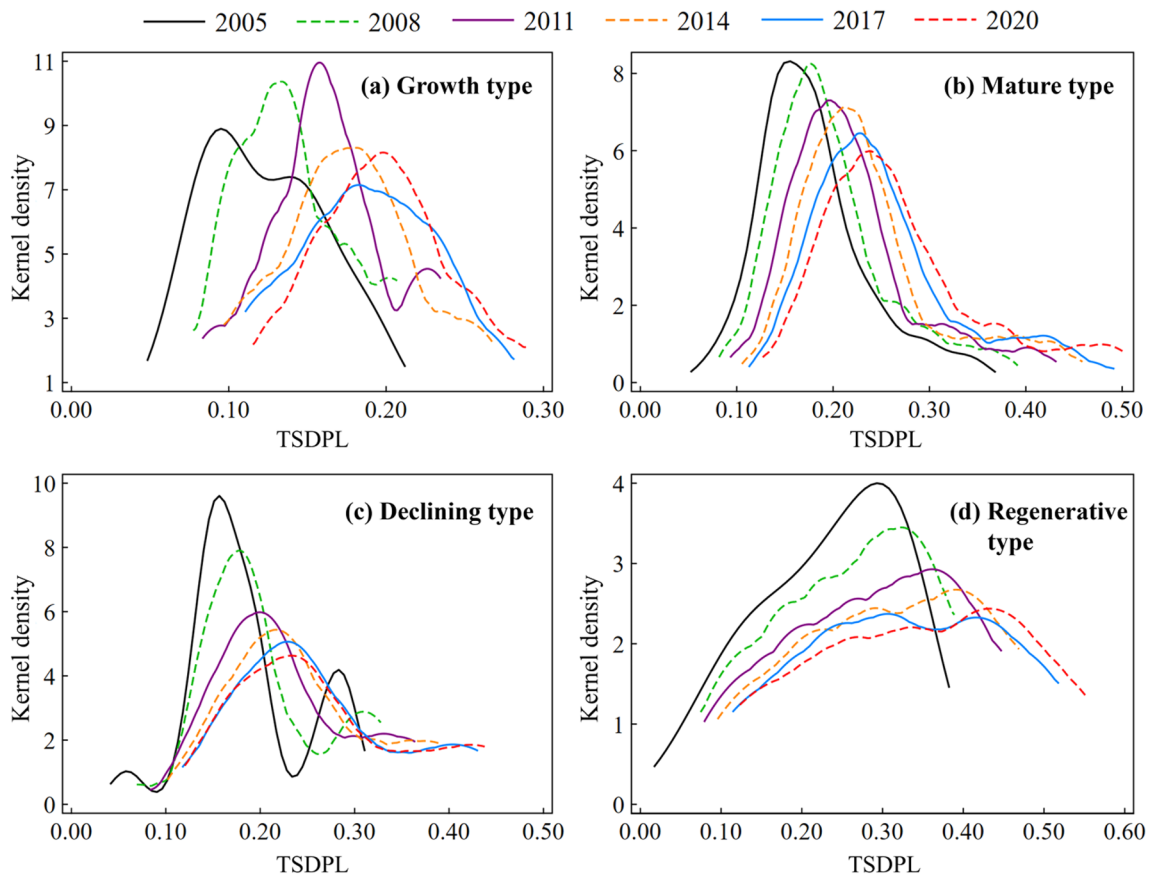


Fig.16. The kernel density estimation of TSDPL of cities in different development stages.

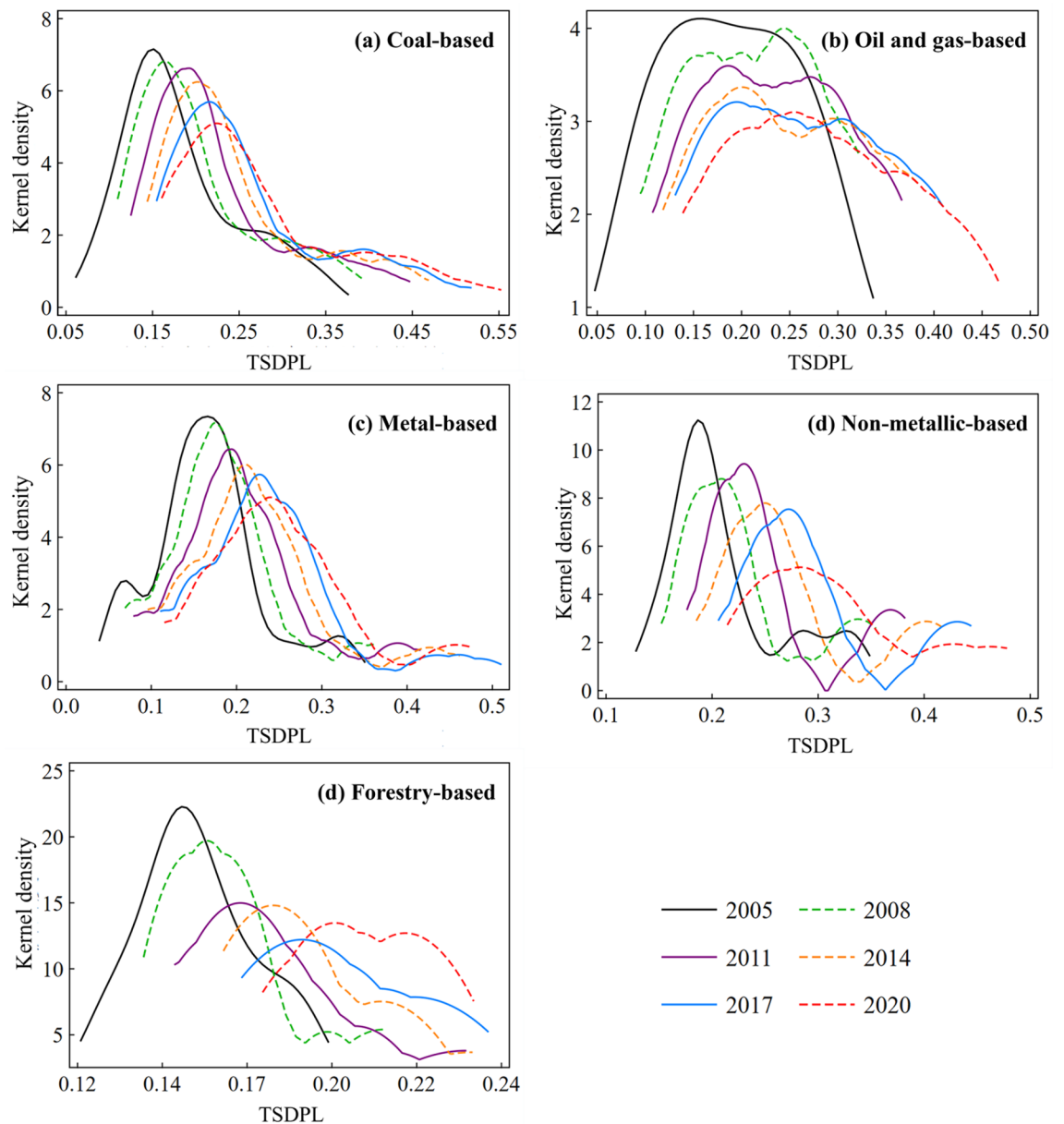
③ By geographical region, all regions except the northeast exhibited rightward tail shifts with decreasing left-tail proportions, indicating improvement in both high and low-value areas alongside a reduced share of low-performing cities. The northeastern region displayed no clear tail movement pattern.

### Discussion

#### Discussion on the spatiotemporal patterns of TSDPL

(1) The shaping of TSDPL patterns by macro-level strategies and contextual factors.

This study finds that the TSDPL exhibits an overall spatial pattern characterized by "higher levels in the east than the west, and higher levels in the south than the north," with its center of gravity shifting towards the

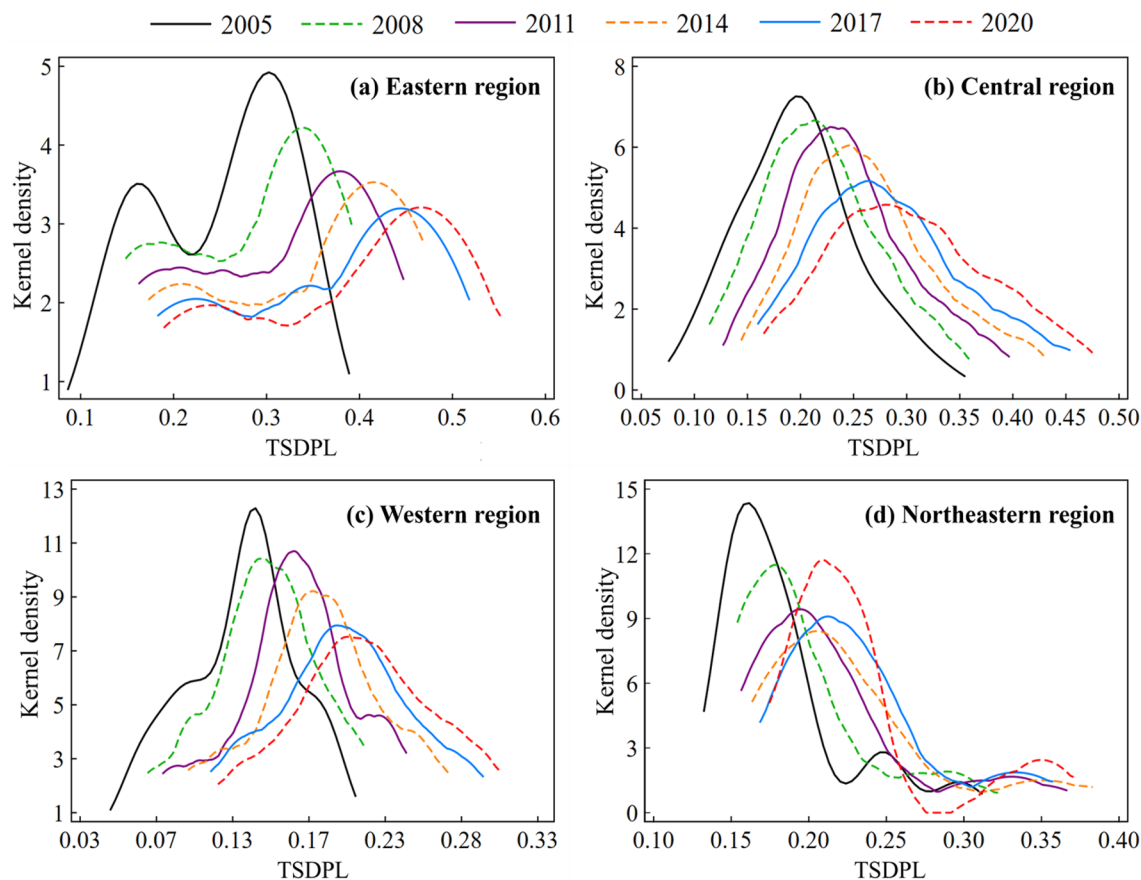


**Fig.17.** The kernel density estimation of TSDPL of cities with different resource types.

southwest. The formation of this pattern stems from the long-term interaction between national regional development strategies and local resource endowments.

The high TSDPL agglomeration in the eastern region benefits from the coastal priority development strategy, which facilitated foreign investment inflows, industrial upgrading, and talent concentration. This laid a structural foundation for achieving a high level of synergy between development and protection in this region. Driven by the "Rise of Central China" strategy, the central region has achieved rapid economic growth by undertaking industrial relocation. However, the accompanying increase in development intensity has correspondingly heightened ecological protection pressures. Consequently, while the central region demonstrates a "medium-high" overall level, there remains room for improvement in the coordination of protection efforts. Although the western region has experienced relatively rapid growth, it is constrained by both a fragile ecological baseline and a traditional development model. As a result, its overall TSDPL remains at a relatively low level. The northeastern region, grappling with issues such as a singular industrial structure, persistent population outflow, and path dependency in development, shows weak growth in TSDPL and even exhibits localized decline.

The trend of the center of gravity shifting southwest reflects the driving effect of national strategies like the "Western Development Strategy" and the "Yangtze River Economic Belt" on enhancing the development momentum and spatial governance capacity of inland regions.



**Fig. 18.** The kernel density estimation of TSDPL of cities in different distribution regions.

(2) Interpretation of findings from theoretical perspectives.

From the perspective of regional resilience theory, regenerative type cities and those in the eastern region demonstrate higher TSDPL, reflecting their systemic resilience characterized by diversified economic structures and flexible institutions, which enable them to withstand external shocks and achieve transformation. In contrast, declining type cities and some in the northeastern region exhibit insufficient resilience, making them prone to development path lock-in.

Examined through the lens of RBCs transition theory, this study's categorization into growth, mature, declining, and regenerative stages aligns closely with transition cycle theory. The results indicate that the development index generally dominates from the growth to declining stages. Upon entering the regenerative stage, however, breaking the "resource curse" relies on innovation and industrial diversification to propel high-quality development that equally prioritizes development and protection. Non-metallic-based cities, possessing greater potential for industrial chain extension (e.g., in building materials, chemicals), show a more pronounced improvement in TSDPL compared to coal-based cities. This validates the transitional advantage of the "industrial linkage-based diversification" pathway.

Under the framework of sustainable development, differences in TSDPL essentially mirror disparities in the effectiveness of local "development-protection" synergistic governance. Cities with high TSDPL have typically established more effective systems for environmental regulation, spatial control, and green technology application. This enables them to systematically translate national strategies (e.g., the dual carbon goals of carbon peak and carbon neutrality) into localized spatial policies and practices.

(3) The underlying logic of differentiated development trajectories.

First, the stage of development constitutes a fundamental constraint. Growth type cities are in the phase of resource exploitation and expansion, exhibiting strong development momentum but relatively lagging ecological awareness and protection capabilities. Declining type cities face resource depletion and waning momentum, with their capacity for protection investment also constrained by financial limitations. In contrast, regenerative type cities, having undergone prior accumulation and strategic restructuring, have embarked on a positive path driven by innovation and synergistic development and protection.

Second, the type of resource influences the space for transition. Cities dependent on coal, oil, and gas face greater transition resistance due to the low industrial linkage and strong negative environmental externalities associated with energy resources. Cities based on metals and non-metals, however, find it easier to integrate with downstream manufacturing industries, offering a broader scope for industrial chain expansion. Forestry-based cities, despite possessing a relatively sound foundation for ecological protection, encounter significant challenges in transforming their development drivers.

Finally, geographical location shapes development opportunities. Cities in the eastern region, leveraging their coastal openness and market advantages, are more adept at attracting green investments and high-end production factors. Cities in the central and western regions, meanwhile, depend more heavily on national policy support and fiscal transfers. Consequently, the improvement of their TSDPL is closely tied to the continuity and implementation intensity of macro-level policies.

### Policy recommendations and international implications based on typological differences

#### (1) Differentiated policy orientations: tailored strategies based on spatial agglomeration types.

For "high-high" agglomeration areas (e.g., Shandong, Jiangsu), policies should facilitate a shift from scale expansion to quality enhancement, allowing these regions to serve as demonstrative "transition pioneers." The focus should be on areas such as realizing the value of ecological products, optimizing existing construction land use, and promoting green technologies. The goal is to cultivate a refined governance model that synergizes development and protection while enhancing their capacity to radiate positive influence and drive development in neighboring areas.

For "low-low" agglomeration areas (e.g., Gansu, Western Inner Mongolia), policy must center on "strengthening foundations and breaking bottlenecks." This involves increasing central fiscal investment and funding for green infrastructure, prioritizing the containment of ecological degradation, pollution control, and securing basic livelihoods. At the industrial level, stringent environmental access standards should be applied. Mechanisms such as "enclave economy" models and targeted regional assistance partnerships should be explored to integrate these areas into regional green industrial chains, thereby preventing them from falling into a low-level development trap.

For "high-low" isolated cities (e.g., Tangshan), attention should be paid to the development gap with their surrounding regions. Regional coordination mechanisms, such as ecological compensation and industrial collaboration parks, should be utilized to transform localized advantages into regional collective momentum, thereby mitigating the risks of spatial development imbalance and unsustainable isolated growth.

#### (2) Targeted governance pathways tailored to regional and typological differences.

From a regional standpoint, the eastern region should reinforce innovation-driven growth and leadership in standards-setting to promote a systematic enhancement of TSDPL from "quantity" to "quality." The central region needs to implement rigorous ecological controls during the process of industrial transfer, thereby actualizing the principle of "protection within development." The western region must adhere to ecological priorities, exploring distinctive transition pathways characterized by "development within protection." The northeastern region, in turn, must focus on institutional and mechanistic reforms as a breakthrough to dismantle path dependence and enhance the efficacy of spatial governance.

Policy interventions should be differentiated according to developmental stages. Growth type cities should establish strict ceilings on development intensity and environmental access thresholds to prevent extensive, low-efficiency expansion. Mature type cities require forward-looking planning, guiding industrial diversification through instruments such as the establishment of transition funds. Declining type cities should prioritize safeguarding people's livelihoods and ecological restoration, promoting alternative development models such as rewilding or the integration of culture and tourism. Regenerative type cities should concentrate on advancing institutional innovation to construct a green, endogenous growth mechanism.

Guidance should vary based on resource types. Cities reliant on coal, oil, and gas should focus on advancing clean energy transition and cultivating successor industries. Cities centered on metal and non-metal resources should prioritize extending industrial chains and establishing circular economy systems. Forestry-based cities, while upholding conservation as the foremost principle, should develop non-timber industries—such as understory economy and ecotourism—in a systematic and orderly manner.

#### (3) Implications for the transition of international resource-based regions.

The core value of the TSDPL measurement framework constructed in this study lies in providing an integrated diagnostic tool that coordinates economic development, ecological protection, and sustainable resource utilization. It can serve as a reference for international resource-based regions facing similar transition challenges, such as Germany's Ruhr region and the Rust Belt in the United States. When applying this framework across different contexts, researchers or policymakers can, while retaining the core concept of "development-protection" synergy and the multi-dimensional evaluation approach, adapt the specific indicators based on their own national or regional statistical systems, resource characteristics, and policy priorities (e.g., by replacing

or adding key indicators that reflect core local concerns). The flexible application of this framework can facilitate comparative research on sustainable development pathways across different resource-based regions and promote the sharing of transition knowledge and governance dialogues on a global scale.

### Reflection on spatial determinism and implications for future research

This study systematically reveals the spatiotemporal differentiation pattern of TSDPL in China's RBCs. It is also essential to recognize that the spatial distribution of these cities is deeply constrained by their inherent resource endowments and historical development strategies. Therefore, the observed "high-high" or "low-low" agglomeration phenomena, to some extent, mirror this foundational "resource geography" pattern. Merely demonstrating such spatial correlations would offer limited independent academic contribution.

However, the core value of this study lies precisely in moving beyond a static, geographically deterministic perspective. While acknowledging the initial resource constraints, it uncovers the following findings with greater policy and theoretical significance:

- (1) Significant intra-group heterogeneity: Significant disparities in TSDPL persist even within groups of cities sharing similar resource types or comparable development stages. This indicates that local factors play a crucial role in shaping transition performance.
- (2) Dynamic spatial evolutionary characteristics: Dynamic patterns such as the migration of the TSDPL gravity center and the "locking-in" or "contraction" of hot/cold spots cannot be explained solely by static resource distribution. These patterns highlight the influence of agential factors—such as local governance capacity, industrial policies, and institutional innovation—on development pathways.
- (3) Divergent overall trend: Kernel density analysis shows that the TSDPL gap among cities continues to widen and exhibits polarization, suggesting that different cities have embarked on distinct transition trajectories—some advancing toward sustainable development while others remain mired in resource dependency.

This study primarily focuses on the systematic description and quantitative assessment of TSDPL patterns and has not yet delved into the underlying causal mechanisms. For instance, while we identified the "high-high" agglomeration in the Shandong city cluster, we did not quantitatively analyze the specific contributions of factors such as local industrial policies, environmental regulations, or fiscal capacity. Future research could advance in the following directions: ① Employ methods like qualitative comparative analysis, in-depth case studies, or panel econometric models to identify key policy variables and institutional conditions influencing TSDPL. ② Systematically investigate how factors such as local governance, industrial diversification, innovation systems, and path dependence enable some cities to overcome resource constraints while others experience sluggish development. ③ Conduct cross-regional and cross-national comparative studies to test the applicability of the TSDPL framework and explore its adaptation pathways within differentiated institutional environments.

### Conclusion and prospects

This study developed a measurement model to quantify the TSDPL of 110 Chinese RBCs (2005–2020) based on the connotation of TSDP. We analyzed its temporal evolution across the overall sample and various city subtypes, and explored its spatial development, agglomeration patterns, and evolutionary trends. The main conclusions are as follows:

- (1) Between 2005 and 2020, the comprehensive and development indices rose rapidly across all cities, in contrast to the more gradual increase of the protection index, with growth rates for all three declining fluctuately. Analysis of TSDPL across categories revealed a consistent upward trend, with the highest levels observed in regenerative type cities, non-metallic-based cities, and the eastern region, while growth type cities, forestry-based cities, and the western region consistently ranked the lowest.
- (2) Significant spatial disparities in TSDPL were observed, characterized by a "high in the east and south, low in the west and north" pattern. Cities with relatively high and high TSDPL were predominantly concentrated in Hebei and Shandong, whereas those with relatively low and low levels were mainly located in Gansu, Heilongjiang, and Shanxi.
  - ① The gravity center of TSDPL was consistently located in Xinxiang City, Henan Province, and exhibited a general southwestward movement with increasing migration speed. Spatially, the expansion pattern was predominantly aligned along the south–north direction.
  - ② TSDPL displayed significant spatial agglomeration. HH-type cities formed a contiguous cluster spanning Shandong, Jiangsu, Anhui, Hebei, and Henan, while LL-type cities were mainly distributed in Gansu, demonstrating a largely solidified agglomeration pattern. The spatial distribution of hot and cold spots exhibited a clear east–west decreasing gradient. Hot spot areas showed a spatially "locked" evolutionary characteristic, whereas cold spot areas displayed a "shrinking" tendency.
- (3) During the study period, the kernel density curve of TSDPL for the overall sample exhibited a consistent rightward shift in peak position, accompanied by decreasing peak height and increasing distribution width. The curve maintained a primary peak and a distinct right-side peak, with the distance between them gradually narrowing. These dynamics reflect a widening gap and intensifying polarization in TSDPL among

RBCs. Furthermore, kernel density curves of different city types displayed distinct shapes and evolutionary trajectories in terms of peak position, height, and modality, underscoring divergent development pathways across categories.

This study has certain limitations: ① The conclusions are based on a specific TSDPL indicator system and the entropy weight method, meaning the composite evaluation results are influenced by the selection of indicators and weighting approach. ② The research primarily involves descriptive and correlational analyses and does not uncover the causal mechanisms underlying the observed patterns. ③ The use of linear interpolation to fill a small number of missing data points may introduce minor errors. Meanwhile, subtle adjustments in the statistical caliber of yearbook data could potentially compromise the accuracy of cross-period comparisons. Future research could deepen the inquiry in the following directions: ① Employ qualitative comparative analysis or paired case studies to identify the key policy mixes and institutional factors leading to differentiated transition performance. ② Construct panel econometric models to quantitatively examine the impacts of factors such as local governance, economic structure, and external capital on TSDPL. ③ Utilize system dynamics models to simulate the evolutionary trajectory of TSDPL under different policy scenarios, thereby providing support for policy pre-assessment.

## Data availability

The datasets generated and/or analysed during the current study are not publicly available due to confidentiality requirements but are available from the corresponding author on reasonable request.

Received: 12 August 2025; Accepted: 3 February 2026

Published online: 29 March 2026

## References

- Meng, Q. & Chen, X. Research on multi-dimensional statistical measurement and driving factors of carbon emission differences in resource-based cities. *Urban Probl.* **6**, 25–34 (2024).
- Li, Q., Zeng, F., Liu, S., Yang, M. & Xu, F. The effects of China's sustainable development policy for resource-based cities on local industrial transformation. *Resour. Policy* **71**, 101940 (2021).
- Xu, W., Zheng, J., Zhou, J., Xilin, C. & Liu, C. Transformation performance characteristics of resource-based cities and their carbon emission reduction effects. *J. Nat. Resour.* **38**(1), 39–57 (2023).
- Zhu, H. et al. Thoughts on regional path of promoting comprehensive demonstration of low-carbon energy technology under “dual carbon” goals. *Bull. Chin. Acad. Sci.* **37**(4), 559–566 (2022).
- Liao, Q. et al. Carbon emission characteristics of resource-based cities in China. *Iran. J. Sci. Technol. Trans. Civ. Eng.* **46**(6), 4579–4591 (2022).
- Zhao, R. et al. Key issues in natural resource management under carbon emission peak and carbon neutrality targets. *J. Nat. Resour.* **37**(5), 1123–1136 (2022).
- Fan, J. The strategy of major function oriented zoning and the optimization of territorial development patterns. *Bull. Chin. Acad. Sci.* **28**(2), 193–206 (2013).
- Huang, X., Chen, Y., Zhao, Y., Shi, M. & Li, T. Optimization on land spatial development pattern in the Yellow River Basin: From the perspective of land development intensity. *Geogr. Res.* **40**(6), 1554–1564 (2021).
- Zhao, Y., Liu, Y. & Long, K. Features and influencing factors of urban land development intensity of urban land resources in the Yangtze River Delta. *Resour. Environ. Yangtze Basin* **21**(12), 1480–1485 (2012).
- Tang, Z. & Fu, L. Study on urban density zoning—Taking Shenzhen special economic zone as an example. *Urban Plan. Forum* **4**, 1–9 (2003).
- Tang, B. & Yiu, C. Space and scale: A study of development intensity and housing price in Hong Kong. *Landsc. Urban Plan.* **96**(3), 172–182 (2010).
- Tan, S., Liu, Q. & Han, S. Spatial-temporal evolution of coupling relationship between land development intensity and resources environment carrying capacity in China. *J. Environ. Manage.* **301**, 113778 (2022).
- Tang, C. & Sun, W. Comprehensive evaluation of land spatial development suitability of the Yangtze River Basin. *Acta Geogr. Sin.* **67**(12), 1587–1598 (2012).
- Zhou, B., Bao, H. & Peng, B. Evaluation on exploitative of intensity of land resources in the Yangtze River Delta region. *Sci. Geogr. Sin.* **20**(3), 218–223 (2000).
- Liu, Y., Liu, J., He, C. & Feng, Y. Evolution of the coupling relationship between regional development strength and resource environment level in China. *Geogr. Res.* **32**(3), 507–517 (2013).
- Hu, J., Huang, Y. & Du, J. The impact of urban development intensity on ecological carrying capacity: A case study of ecologically fragile areas. *Int. J. Environ. Res. Public Health* **18**(13), 7094 (2021).
- Zhu, X., Huang, Z., Zhang, T. & Gao, J. Spatiotemporal coupling characteristics and driving factors of land development intensity and ecological bearing capacity in resource-based cities—A case study of Ma' anshan City. *Res. Soil Water Conserv.* **27**(4), 317–326 (2020).
- Wu, D., Hu, Y., Liu, Y. & Liu, Y. Empirical study on the coupling coordination between development intensity and resources-and-environment carrying capacity of core cities in Pearl River Delta. *J. Nat. Resour.* **35**(1), 82–94 (2020).
- Yang, Z., Wang, S., Guo, M., Tian, J. & Zhang, Y. Spatiotemporal differentiation of territorial space development intensity and its habitat quality response in Northeast China. *Land* **10**(6), 573 (2021).
- Chen, Q. & Wang, Z. Spatio-temporal coupling and interactive effects of land development intensity and economic resilience in the Wuling Mountains Area. *Econ. Geogr.* **43**(4), 41–50 (2023).
- Kong, X., Jiang, X., Liu, Y. & Jin, Z. Spatiotemporal coupling between territorial space development intensity and resource environmental carrying capacity and its planning implications: A case study of Jiangsu Province. *Zhongguo Tu Di Ke Xue* **34**(6), 10–17 (2020).
- Zhang, Z. & He, D. Interaction between environmental protection and economic development: A case of Chongming, Shanghai. *World Reg. Stud.* **32**(4), 84–95 (2023).
- Zhuang, Y., Yang, H., Guo, R., Zeng, G. & Ma, X. Environmental indicators system for the construction of eco-island—A case study of Chongming Island. *Resour. Environ. Yangtze Basin* **18**(10), 937–942 (2009).
- Guo, H. & Hu, C. Ecological environmental protection and high-quality industrial economic development in the Yellow River Basin: Coupled measurement and spatio-temporal evolution. *Ningxia Shehui Kexue* **6**, 132–142 (2022).

25. Xu, J. Research on coordinated development of high-quality economic development and ecological environmental protection under the “dual carbon” goal—A case study of Beijing-Tianjing-Heibei region. *Reform Econ. Syst.* **1**, 61–69 (2023).
26. Deng, Z., Zong, S., Su, C. & Chen, Z. Research on coupling coordination development between ecological civilization construction and new urbanization and its driving forces in the Yangtze River economic zone. *Econ. Geogr.* **39**(10), 78–86 (2019).
27. Kong, F., Yang, W. & Xu, C. Coordinated relationship and influencing factors of ecological environment and socio-economic coupling of urban agglomeration around Hangzhou Bay in China. *Acta Ecol. Sin.* **43**(6), 2287–2297 (2023).
28. Li, W. & Xi, Y. Research on provincial ecological civilization construction evaluation under the efficiency perspective. *Acta Ecol. Sin.* **36**(22), 7354–7363 (2016).
29. Zhang, J. & Xia, H. Construction and evaluation method of ecological civilization index system. *Stat. Decis.* **21**, 60–63 (2009).
30. Cheng, J., Chen, J. & Li, Y. Research on the measurement of China’s ecological civilization development level. *J. Quant. Technol. Econ.* **30**(7), 36–50 (2013).
31. Zhang, J. & Xia, T. The change and reconstruction of spatial planning system under the goal of modern national governance. *J. Nat. Resour.* **34**(10), 2040–2050 (2019).
32. Lengyel, J., Roux, S. & Alvanides, S. Multivariate analysis of socioeconomic profiles in the Ruhr area, Germany. *J. Maps.* **10**(3), 576–584 (2022).
33. Zepp, H. Regional green belts in the Ruhr region a planning concept revisited in view of ecosystem services. *Erdkunde* **72**(1), 1–21 (2018).
34. Walling, D., Sadler, R. & Lafreniere, D. Lessons from U.S. Rust Belt cities for equitable low-growth futures. *Urban Res. Pract.* **14**(4), 471–482 (2021).
35. Armstrong, B. Industrial policy and local economic transformation: Evidence from the US Rust Belt. *Econ. Dev. Q.* **35**(3), 181–196 (2021).
36. Li, J. & Li, J. Difference and formation mechanism of people’s livelihood and well-being development in Guangdong Province. *Sci. Geogr. Sin.* **43**(3), 500–508 (2023).
37. Yang, J. & Huang, X. The 30 m annual land cover dataset and its dynamics in China from 1990 to 2019. *Earth Syst. Sci. Data* **13**(8), 3907–3925 (2021).
38. Feng, X. et al. Spatiotemporal pattern and coordinating development characteristics of carbon emission performance and land use intensity in the Yangtze River Delta Urban Agglomeration. *Trans. Chin. Soc. Agric. Eng.* **39**(3), 208–218 (2023).
39. Yan, H. et al. Increasing human-perceived temperature exacerbated by urbanization in China’s major cities: Spatiotemporal trends and associated driving factors. *Sustain. Cities Soc.* **18**, 106034 (2025).
40. Banadkouki, M. R. Z. Selection of strategies to improve energy efficiency in industry: A hybrid approach using entropy weight method and fuzzy TOPSIS. *Energy* **279**, 128070 (2023).
41. Cheng, T., Zhao, Y. & Zhao, C. Exploring the spatio-temporal evolution of economic resilience in Chinese cities during the COVID-19 crisis. *Sustain. Cities Soc.* **84**, 103997 (2022).
42. Rogerson, P. Historical change in the large-scale population distribution of the United States. *Appl. Geogr.* **136**, 102563 (2021).
43. Zhao, H., Liu, Y., Lindley, S., Meng, F. & Niu, M. Change, mechanism, and response of pollutant discharge pattern resulting from manufacturing industrial transfer: A case study of the Pan-Yangtze River Delta, China. *J. Clean. Prod.* **244**, 118587 (2020).
44. Duman, Z. et al. Exploring the spatiotemporal pattern evolution of carbon emissions and air pollution in Chinese cities. *J. Environ. Manage.* **345**, 118870 (2023).
45. Yin, Z. et al. Spatial-temporal evolution patterns of influenza incidence in Xinjiang Prefecture from 2014 to 2023 based on GIS. *Sci. Rep.* **14**(1), 21496 (2024).
46. Kim, D. Exploratory study on the spatial relationship between emerging infectious diseases and urban characteristics: Cases from Korea. *Sustain. Cities Soc.* **66**, 102672 (2021).
47. Moran, P. A. P. Notes on continuous stochastic phenomena. *Biometrika* **37**(1–2), 17–23 (1950).
48. Anselin, L. Local indicators of spatial association: LISA. *Geogr. Anal.* **27**(2), 93–115 (1995).
49. Getis, A. & Ord, J. K. The analysis of spatial association by use of distance statistics. *Geogr. Anal.* **24**(3), 189–206 (1992).
50. Huang, J., Li, Q., Du, M. & Chen, X. Spatial and temporal variation of economic resilience and its drivers: Evidence from Chinese cities. *Front. Environ. Sci.* **11**, 1109857 (2023).
51. Sheather, S. Density estimation. *Stat. Sci.* **19**(4), 588–597 (2004).
52. Zhang, J., Shi, H. & Dong, Z. Real-time remaining useful life prediction based on relative density kernel estimation. *J. Vib. Shock* **41**(22), 308–318 (2022).
53. Silverman, B. W. *Density estimation for statistics and data analysis* (Chapman and Hall, 1986).

## Author contributions

Li Ji: Writing—original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. Huadong Gao: Writing—review & editing, Validation, Supervision, Methodology, Conceptualization. Longgao Chen: Writing—review & editing. Jihong Dong: Writing—review & editing.

## Declaration

### Competing interests

The authors declare no competing interests.

### Additional information

**Correspondence** and requests for materials should be addressed to H.G.

**Reprints and permissions information** is available at [www.nature.com/reprints](http://www.nature.com/reprints).

**Publisher’s note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

**Open Access** This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by-nc-nd/4.0/>.

© The Author(s) 2026