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Evolutionary characteristics, regional differences and spatial effects of coupled coordination of rural revitalization, new-type urbanization and ecological environment in China

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Rural revitalization (R), new-type urbanization (U) and the ecological environment (E) are a unity of complementary advantages and mutual promotion and coexistence, the coupling and coordination of the three is the key to realizing the Chinese modernization and the harmonious coexistence of human beings and nature. Based on China's provincial panel data from 2011 to 2022, this paper constructed a comprehensive evaluation index for the R-U-E system, using the entropy method, coupled coordination model, Dagum's Gini coefficient, kernel density estimation, spatial correlation analysis, and spatial Durbin model to explore the level of comprehensive development, spatial-temporal evolutionary characteristics of coupled coordination, regional differences and spatial effects of the three systems. The following results were observed: (1) The comprehensive index of rural revitalizationand new-type urbanization exhibits a growing trend and significant regional differences, with East China outperforming other regions, but the average value of below 0.5 needs to be further improved. The ecological environment index exhibits a smoother growth trend, higher in South China than in other regions. (2) The level of R-U-E coupling coordination has increased year on year, from barely coordinated to primary coordination. (3) The spatial imbalance in coupling coordination has improved both nationally and in the seven regions, with the largest intra-regional differences in South China and the smallest intra-regional differences in Central China. The differences between the Northeast and Central China regions exhibit a widening trend, while the differences between all other regions exhibit a decreasing trend. Interregional variations are the main factor affecting overall variance, but their impact on the overall variance is gradually diminishing. (4) The level of coupling coordination has obvious spatial correlation, and the "high-high" and "low-low" cluster aggregation characteristics was evident. (5) Government behavior and the levels of economic growth, human capital, and digitization significantly contribute to the coupled and coordinated development of the region and, at the same time, have a significant spatial spillover effect on neighboring provinces; the degree of openness to the outside world contributed to the coordinated development of the region, while it had an inhibitory effect on the neighboring provinces; and the drive to innovate has only a certain contributing effect on the neighboring regions. Targeted policy measures in response to this paper's empirical findings may provide policymakers with a reference point for achieving regional sustainable development goals.

KEYWORDS

rural revitalization, new-type urbanization, ecological environment, coupling coordination, regional differences, spatial effect

1 Introduction

Since the reform and opening up, China has made remarkable socio-economic achievements, and the process of industrialization and urbanization has been further accelerated. In 2022, the urbanization rate has reached 65.22%. However, the continuing unilateral export of rural factors of production to the cities has also resulted in uneven development between urban and rural areas and has exerted enormous pressure on the ecological environment (Shao and Leng, 2022). The 18th CPC National Congress put forward a new type of people-centered urbanization, which emphasizes people-centeredness and promotes high-quality and coordinated urbanization through urban-rural coordination, urban-rural integration, industry-city interaction, conservation and intensification, ecological livability and harmonious development. In order to further narrow the gap between urban and rural areas and achieve common prosperity, the 19th CPC National Congress Report put forward a rural revitalization strategy that includes industrial revitalization, cultural revitalization, ecological revitalization, organizational revitalization, and talent revitalization, and emphasized the need to achieve a "dual-wheel drive for rural revitalization and new urbanization" in the published Rural Revitalization Strategic Plan (2018–2022), and proposed that integrated urban and rural development should be synergistically developed with ecological environment and mutually promoted. The 20th CPC National Congress proposed that in order to achieve Chinese-style modernization, the concept of harmonious coexistence between human beings and nature should be carried out throughout the entire process of economic and social development, and a new pattern of green development should be promoted. Therefore, the ecological environment is the main element in realizing integrated urban and rural development. In the new development phase, the process of rural revitalization and new urbanization should alter its dependence on extreme extractive activities and take the road of healthy and sustainable development that is green, low-carbon, highly efficient and intensive, and compatible with the carrying capacity of resources and the environment (Guo L. X. et al., 2023). The coordinated development of cities, villages and the environment has become the key to achieving sustainable regional development. (1) What is the level of integrated development of the three systems of rural revitalization, new urbanization and ecology in China, including the trends and characteristics of their spatial and temporal evolution? (2) What are the characteristics of the spatial and temporal evolution of the coupled coordination of the three, their regional differences, and the sources of such differences? (3) What are the driving mechanisms for the coupling and coordination of the three, and what spatial effects do they exhibit? (4) What measures can be taken to sustainably promote a desirable level of coupling coordination and reduce regional disparities? Clarifying these issues is conducive to innovating the realization path of urban-rural integration and high-quality development, providing innovative ideas for cracking the imbalance between urban and rural development in various regions, and providing guidance for green urban-rural synergistic development.

This paper selects panel data from 31 provinces in China from 2011 to 2022, constructs the interaction mechanisms of the three and construct a comprehensive evaluation index system. The spatio-temporal evolutionary characteristics and regional differences of the three couplings were analyzed using the entropy method, the coupled coordination model, the Dagum Gini coefficient, and the kernel density estimation method. Spatial autocorrelation and spatial Durbin models are used to reveal the spatial effects of the coupled coordination. Summarizes the trend characteristics and regional differences in the coordinated development of R-U-E coupling in China and proposes strategies to promote coordinated development, while providing a policy basis for urban-rural integration and sustainable regional development. The research framework of this paper is shown in Figure 1.

2 Literature review

Domestic research on the relationship between rural revitalization, new urbanization and the ecological environment mainly focuses on one of the systems or between the two systems, with urban-rural relations in particular being the most numerous. Firstly, the relationship between rural revitalization and new urbanization has gone through several stages, such as theoretical changes in urban-rural relations (Davoudi, 2002), the mechanism of urban-rural integration (Epstein and Jezeph, 2001), the measurement of urban-rural coordinated development (Fang, 2022), and the strategy of urban-rural coordinated development (Yang and Deng, 2023; Somanje et al., 2020). The empirical research focuses on urban-rural development patterns in different regions and spatial scales and quantitatively analyzes the spatial distribution (Cui and Li, 2024; Zhang and Wang, 2022; Wang and Han, 2023), regional differences and realization paths of the coordinated development of new urbanization and rural revitalization (He, 2018a; Zhou et al., 2023; Cong et al., 2024). The study found that there is a positive interaction between the two that promotes and supports each other. Secondly, an earlier study of the relationship between urbanization and ecology was the environmental Kuznets curve hypothesis, which suggests an inverted U-shaped relationship between environmental pollution and economic growth (Grossman and Krueger, 1991). Scholars often use the "pressure-state-response" model to explore the relationship between human economic activity and the ecosystem, and the study found that urbanization puts a certain pressure on the

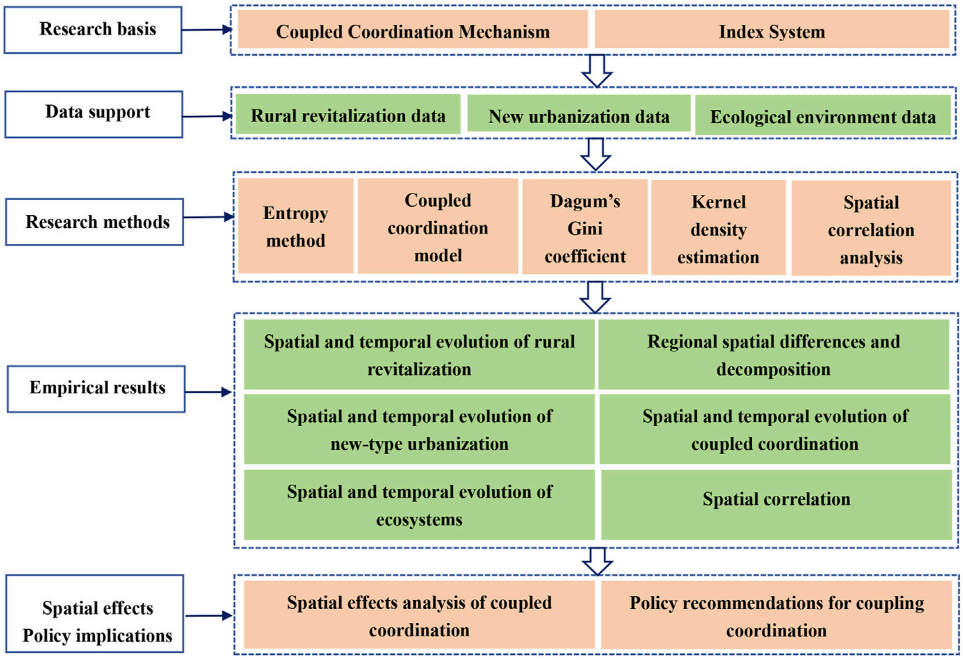

FIGURE 1
Research framework.

ecological environment, that the ecological environment imposes constraints on urbanization, that the ecological environment is the material basis of urbanization, and that ecological protection should be increased in the process of urbanization (Grossman and Krueger, 1995; Yang et al., 2020). Thirdly, studies on the relationship between rural revitalization and the ecological environment have focused on emphasizing that ecological revitalization is an important element of rural revitalization. Ecological livability is the key, and a foundation for rural revitalization and ecological priority must be established for implementation of the rural revitalization strategy (Lu et al., 2022). Rural revitalization will bring serious challenges to the rural ecological environment in the course of industrial development, and ecological environmental protection should be strengthened in the course of implementing rural revitalization (Zhong et al., 2020). The results of the research on the coordination relationship among the three mainly include the fact that the level of coordination among rural revitalization, new urbanization and ecological environment in the three northeastern provinces has increased, but there are large differences among cities (Zhu et al., 2022). The degree of interaction among the three major systems in Yunnan Province is gradually increasing, and the spatial variability of the coupling types is gradually becoming smaller (Guo Y. et al, 2023). Rural revitalization, new urbanization and ecological environment coupling and coordination in the Yellow River Basin have slowed down, with obvious spatial differentiation (Zhang and Yang, 2024). The level of coupling and coordination of the three major systems in China shows a fluctuating upward trend from 2011 to 2020 (Zhu et al., 2022). The methods used in the empirical analysis focus on entropy method, coupled coordination model, gray correlation model, kernel density estimation, relative development degree model and dagum Gini coefficient (Xie et al., 2022; Song et al., 2024; Ma et al., 2024).

The three systems of rural revitalization, new urbanization and ecological environment encompass multiple aspects of population, economy, society, resources and ecology, and scholars have explored the factors influencing the coordinated development of the three. The level of economic development, as the material basis of regional development and ecological governance, is the primary factor of concern for scholars, and it is generally recognized that economic development is an effective driving force for the coordinated development of regional urban and rural areas, with important impacts on rural and urban subsystems (Jiang and Han, 2023). Innovation is a driving force for regional socio-economic development, and some scholars have found that scientific and technological innovation can play a role in rural revitalization in the form of knowledge, technology and product innovation (Liu J. et al., 2024). Innovation can contribute to the modernization of agriculture and rural areas by empowering new forms of productivity (Bian and Wei, 2023). Science and technology innovation is the key support for the high quality development of the region in the new journey (Wu G. et al., 2024). The government plays a very important role in realizing urban-rural integration, and some scholars have found that government environmental governance has a positive impact on the efficiency of the green economy (Wu, 2024). Local government interventions can significantly improve energy use efficiency (Wu S. J. et al., 2024). A series of Chinese policies have promoted sustainable rural development (Guo and Li, 2024). As a product of the new round of scientific and technological revolution and industrial change, the digital economy is playing an active role in "empowering" various fields, sectors and relationships of socio-economic activities (Sun et al., 2024),Scholars believe that the development of digital economy can effectively reduce the intensity of regional carbon emissions through the effects of industrial structure optimization and resource allocation (Lyuet al., 2023). The digital economy is seen as a key engine for the

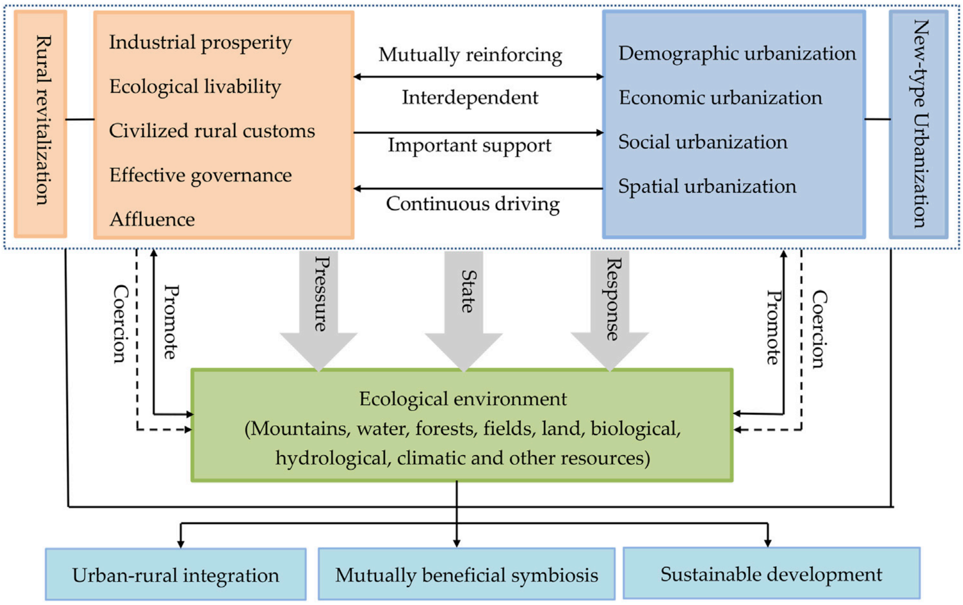

FIGURE 2
The coupling mechanism of the rural revitalization, new-type urbanization and the ecological environment.

modernization of agriculture (Yang, 2024). Digital infrastructure development is an important pathway for promoting shared prosperity and reducing regional income disparities (Liu Y. et al., 2024). The digital global value china participation can reduce energy resilience (Zhang et al., 2024b). The impact of digital economy on new urbanization is characterized by increasing marginal utility (Li et al., 2024). Local governments play a key role in integrating green development (Zhang et al., 2024c). It has also been argued that educational development can contribute to sustainable regional development by fostering human capital (Kaganovich and Zilcha, 1999). Improvement of the higher education system can promote the development of new urbanization (Wang et al., 2022). Talent revitalization is the key to rural revitalization, and the cultivation of rural human capital should be increased (Li et al., 2024), For the analysis of factors affecting the coupling of rural revitalization, new urbanization and ecological environment, individual domestic scholars have been involved, mainly focusing on the level of economic development, the level of opening up to the outside world, the government's ability and the vitality of tourism, and the methods used mainly include the Tobit model and the multiple linear regression model (Zhang and Yang, 2024).

In summary, there is a close relationship between rural revitalization, new urbanization and the ecological environment, which is of great significance to the sustainable development of the region. Although there has been some scholarship on the coordinated development of the three, there is still some room for exploration. Firstly, the existing research mainly focuses on the spatio-temporal characteristics of the development level of a particular system or the coupled and coordinated relationship between two systems. However, empirical analysis of the coupled and coordinated relationship between the three is lacking. Secondly, most of the existing studies have analyzed the differences within the Yellow River Basin or a particular province but have not studied such relationships and differences on the national level or among the seven regions. Studies on the sources of regional variability and intrinsic correlations regarding the level of coordinated development of urban-rural coupling are also lacking. Thirdly, existing studies have not included spatial factors in their analyses of the factors affecting coupled coordination and lack empirical exploration of spatial effects.

3 Coupled coordination mechanism

Rural revitalization, new urbanization and ecology comprise an organic unity that is mutually reinforcing and interdependent. The German physicist Haken focused on the similarity of various systems as they change from disorder to order in his proposed theory of synergy (Cai et al., 2021). Based on his theory, this paper constructs a coupled coordination mechanism for the three systems of rural revitalization, new urbanization and ecological environment (Figure 2).

3.1 Rural revitalization and new-type urbanization

Rural revitalization and new urbanization appear to be contradictory, but in fact, a symbiotic relationship of mutual influence and synergistic development exists between them (Jin et al., 2024). The purpose of coordinated development is to narrow the gap between urban and rural areas, address the problem of unbalanced and inadequate development, and promote sustainable development in urban and rural areas.

New-type urbanization is a continuous driving force for rural revitalization (Qiao et al., 2023). New urbanization has resulted in a strong pull on surplus rural labor, and the development of secondary and tertiary industries in towns and cities has broadened employment channels for farmers and raised their incomes. Improved infrastructure and convenient, basic public services have upgraded the quality of life of farmers who have moved to the towns and have also promoted the concentration of the rural population in the towns. The transfer of the rural population to towns and cities has reduced the number of individual operations on arable land, which is conducive to large-scale and mechanized production and innovative business models to improve agricultural output and efficiency (Feng and Sun, 2020). Cities and towns provide support for the countryside, promote the circulation of factors such as capital, technology, human resources, information and modern equipment, increase the added value of agricultural products, promote the integration of the three industries, and modernize agriculture. The gradual transformation of agricultural producers into consumers has expanded the demand in agricultural markets (Tan et al., 2022). Optimizing the allocation of factors of production in rural areas through proximity urbanization, enhancing the radiative role of central towns and strengthening the positive spillover effect on the industrial structure and spatial layout of the countryside are, therefore, key concerns.

Rural revitalization offers an important support for new urbanization (Zhang and Kong, 2021). The development of rural pillar industries and characteristic industries, the extension of the agricultural industry chain, and the transformation and upgrading of rural industries have resulted in greater employment among the rural labor force, promoted the urbanization of the rural population in the vicinity of their homes, and pushed forward the process of new-type urbanization. Protection and restoration of rural ecology and management of human settlements has helped to provide green space and ecological support for the sustainable development of cities and towns (Xu and Wang, 2022). Development in rural areas can enrich the spiritual and cultural life of villagers, improve their moral qualities and ideological concepts, realize the effective combination of traditional rural civilization and modern urban civilization, and provide a humanistic foundation for the development of social urbanization (Liu and Wu, 2024). Rural governance can effectively carry out rural spatial planning and optimize spatial structure, break through urban-rural boundaries and promote the integration of urban and rural functions (Xu M. Y. et al., 2019). Rural residents comprise an extensive consumer market, and the increased affluence of residents has increased demand for education, medical care, pensions, housing, leisure and other products, which, in turn, promotes the prosperity of town industries, the improvement of infrastructure and the enhancement of residents' incomes. This provides the impetus to support the improvement of the quality of life of urban residents.

3.2 Rural revitalization and the ecological environment

A healthy ecological environment offers the greatest advantage for sustaining the rural wealth necessary to drive rural revitalization (He, 2018b). Achieving this will require developing ecological industries, taking the road of green development, adjusting and optimizing the industrial structure, tapping the natural, cultural and tourism elements of the countryside, and realizing the integration of the three industries. Prosperous industries bring huge output and provide abundant material support for the management of the ecological environment. A healthy ecological environment is the most universal factor in the wellbeing of people's livelihoods, and ecological revitalization is an important foundation for comprehensively promoting rural revitalization. Inherent in this is the greening and decarbonization of rural production and lifestyles through the popularization of hygienic toilets and clean energy renovation, as well as other environmental treatments (Wei et al., 2024). In the process of industrial revitalization, there may also be an increase in resource consumption and land use, thus creating ecological constraints and potentially imposing further constraint on rural revitalization through green development (Zhu et al., 2022).

3.3 New-type urbanization and ecological environment

A high-quality ecological environment is an important condition for the sustainable development of new urbanization, which is necessary to lay a solid foundation for the continuous improvement of the ecological environment. The ecological environment forms the material basis for the development of new urbanization, and urbanization takes the protection of the ecological environment and the conservation of resources as a prerequisite; there exists both a promotional and a coercive relationship between the two (Ni, 2024). A healthy ecological environment provides basic protection for human production and life; attracts the concentration of population, industry and factors; promotes the optimization of the industrial structure and the upgrading of the consumption structure; and promotes the sustainable development of urbanization (Deng et al., 2024). Traditional industries have been gradually transformed and upgraded in the process of new urbanization, and high-tech industries have promoted technological innovation and eased the pressure on resources and the environment in the course of industrial development.

Urbanization has created some constraints on the ecosystem. Population growth, economic development, land expansion and trade opening in the process of urbanization will demand ecological resources, which will lead to natural resources tension, ecological landscape destruction and disorderly development of urban space, etc., (Chen et al., 2020). At the same time, the urbanization is also constrained by ecological resources. New-type urbanization emphasizes a people-oriented approach, advocates green development, recycling development and low-carbon development, strengthens ecological environmental protection, and reduces interference and damage to the natural ecological environment caused by human activities, thus forming a green and low-carbon production and life style, while promoting the coupled and coordinated development of urbanization and the ecological environment.

4 Data sources, index system, and research methods

4.1 Data sources

The raw data come from the China Statistical Yearbook, the China Urban Statistical Yearbook, the China Rural Statistical

TABLE 1 The evaluation index system of the R-U-E system.

Target layer	Element layer	Significance of the indicators	Index layer	Unit	Nature	Weight
Rural revitalization	Industrial prosperity	the level of agricultural modernization	Value added in the primary sector	CNY	+	0.081
			Agricultural labor productivity	CNY/ people	+	0.054
			Total power of agricultural machinery *per capita*	kWh	+	0.084
	Ecological livability	the state of a livable and workable habitat	The amount of fertilizer applied per unit of arable land	ton/ hectare	-	0.016
			The amount of pesticide applied per hectare of arable land	ton/ hectare	-	0.034
			The coverage of sanitary latrines	%	+	0.153
			The rate of hardening of village roads	%	+	0.109
	Civilized rural customs	the cultural environment in which villages are being built	The share of education, recreation and entertainment expenditure in consumer expenditure	%	+	0.025
			Number of township cultural stations per 10,000 people	number	+	0.097
			Illiteracy rate	%	+	0.011
			Divorce rate	%	-	0.038
	Effective governance	organizational security and integrated urban-rural governance	Number of village councils per 10,000 people	number	+	0.082
			The urban-rural income ratio	%	-	0.032
			Number of health technicians per 10,000 people	people	+	0.038
	Affluence	the ultimate destination for meeting the needs of farmers for a better life	Per capita net income in the countryside	CNY	+	0.075
			Engel coefficient	%	-	0.023
			Number of cars owned per 100 households	number	+	0.054
New-type urbanization	Demographic urbanization	the process of population concentration in cities and towns	Urbanization rate of the resident population	%	+	0.033
			Urban population density	people/ m^2	+	0.232
			Proportion of employees in the secondary	%	+	0.062
			and tertiary industries			
	Economic urbanization	the efficiency of economic development	Contribution of secondary and tertiary industries	%	+	0.026
			Disposable income of urban residents	CNY	+	0.146
			Retail sales of consumer goods	CNY	+	0.107
	Social urbanization	the accessibility of public services	Number of medical beds per 10,000 people	number	+	0.054
			Urban registered unemployment	%	-	0.058
			Urban water penetration	%	+	0.025
			Urban gas penetration	%	+	0.017
	Spatial urbanization	the spatial use of land	Economic density of the developed area of the cit	CNY/ km^2	+	0.068
			Per capita road area of the city	m^2	+	0.049
			Share of urbanized land in the urban area	%	+	0.069

(Continued on following page)

TABLE 1 (*Continued*) The evaluation index system of the R-U-E system.

Target layer	Element layer	Significance of the indicators	Index layer	Unit	Nature	Weight
Ecological environment	Pressure	comes from industry and industrial wastewater emissions	Industrial wastewater discharge	ton	-	0.039
			Industrial SO_2 emissions	ton	-	0.074
			per capita sewage discharges	ton	-	0.07
			general industrial solid waste generation	ton	-	0.043
	State	the current state of the ecological environment	Per capita green park area	m^2	+	0.081
			forest coverage rate	%	+	0.149
			Green coverage rate in built-up areas	%	+	0.072
	Response	the extent to which human beings have taken measures to improve ecological conditions	Domestic sewage treatment rate	%	+	0.035
			Decontamination rate of urban refuse	%	+	0.041
			Daily treatment capacity of municipal sewage	m^2	+	0.202
			Solid waste treatment rate	%	+	0.172

Yearbook, the China Urban and Rural Construction Statistical Yearbook, the China Social Statistical Yearbook, the China Environmental Statistical Yearbook, provincial statistical yearbooks, and statistical bulletins on national economic and social development. The period is 2011–2022. Some of the missing data are supplemented by the mean imputation method. The data were processed using the [0, 1] standardization method, and the entropy value method was used for the assignment of indicator weights, and the comprehensive index method was used to calculate the comprehensive development level of rural revitalization, new-type urbanization and ecological environment.

4.2 Index system

This paper follows the principles of scientificity, representativeness, systematicity and operability. Applying the National New Urbanization Plan (2021–2035), the "14th Five-Year" New Urbanization Implementation Plan, the Five-Year Action Plan for the In-depth Implementation of the People-Centered New Urbanization Strategy, the Strategic Plan for Rural Revitalization (2018–2022), and the 14th Five-Year Plan for Promoting Rural Modernization, as well as the "Pressure-State-Response (PSR)" model, it draws on relevant research to construct a comprehensive evaluation index system for rural revitalization-new-type urbanization-ecological environment (R-U-E) (Zhang and Yang, 2024; Måns et al., 2016; UN, 2020; Tong, 2000) (Table 1).

4.3 Research methods

4.3.1 Entropy value method

Considering the significance differences for each indicator and overcoming the overlapping information across indicators, the entropy value method was used to assign weights to the indicators. In order to avoid the randomness of subjective assignment, and at the same time to overcome the problem of overlapping information between the indicators, this paper adopts the objective assignment method for the assignment of the indicator weights, and calculates the composite index of each unit of the symbiosis system. The specific measurement steps are as follows:

Firstly, In order to eliminate the dimensional relationship across variables, it is necessary to standardize the raw data of the indicators. Suppose the number of samples is m and the number of indicators is n. The original indicator data matrix is $X = (x_{ij})_{mn}$, where $i = (1, 2, \cdots m)$, $j = (1, 2, \cdots n)$, and x_{ij} is the quantitative value of the jth indicator of the ith sample.

The normalization calculation for positive indicators is outlined in Equation 1, while Equation 2 illustrates the normalization equation for negative indicators.

$$\text{Positive indicators: } x'_{ij} = \left(x_{ij} - x_{min}\right) / \left(x_{max} - x_{min}\right) \tag{1}$$

$$\text{Negative indicators: } x'_{ij} = \left(x_{max} - x_{ij}\right) / \left(x_{max} - x_{min}\right) \tag{2}$$

x_{max} is the maximum value of an indicator, x_{min} is the minimum value of an indicator.

Second, calculate the entropy of information e_j for each indicator x'_{ij} (Equation 3).

$$e_j = -\frac{1}{lnm}\sum_{i=1}^{m}\left[\left(x'_{ij} \Big/ \sum_{i=1}^{m} x'_{ij}\right) ln \left(x'_{ij} \Big/ \sum_{i=1}^{m} x'_{ij}\right)\right] \tag{3}$$

Third, calculate the weight w_j of each indicator x_{ij} (Equation 4).

$$\mathbf{w_j} = \left(\mathbf{1} - \mathbf{e_j}\right) \Big/ \sum_{\mathbf{i=1}}^{\mathbf{n}} \left(\mathbf{1} - \mathbf{e_j}\right) \tag{4}$$

Four, calculate the composite index Y_i (Equation 5).

$$\boldsymbol{Y_i} = \sum_{\boldsymbol{i=1}}^{\boldsymbol{n}} \boldsymbol{w_j x'_{ij}} \tag{5}$$

TABLE 2 Coupling coordination degree classification.

Degree of coupling coordination	Type	Degree of coupling coordination	Type
0 ≤ D ≤ 0.1	Extreme unbalance	0.5 < D ≤ 0.6	Borderline coordination
0.1 < D ≤ 0.2	Serious unbalance	0.6 < D ≤ 0.7	Elementary coordination
0.2 < D ≤ 0.3	Moderate unbalance	0.7 < D ≤ 0.8	Middle rank coordination
0.3 < D ≤ 0.4	Mild unbalance	0.8 < D ≤ 0.9	Well coordination
0.4 < D ≤ 0.5	Borderline unbalance	0.9 < D ≤ 1.0	Superior coordination

4.3.2 Coupled coordination degree model

Coupling refers to the interaction of two or more highly-correlated systems that interact and influence each other (Jiang and Hu, 2021). Coupling Degree reflects the magnitude of the interaction relationship. The Coupling Coordinate Degree measures the degree of benign coupling in a coupled relationship and reflects the overall effectiveness of the system. Based on the coupled coordination model, this paper constructs a coupled coordination model of rural revitalization, new-type urbanization and ecological environment on the basis of existing research to quantitatively measure the coupling effect among the three. The formula is as follows (Equations 6–8):

$$C = 3\frac{\sqrt[3]{RUE}}{R+U+E} \tag{6}$$

$$T = \alpha R + \beta U + \gamma e \tag{7}$$

$$D = \sqrt[2]{C \times T} \tag{8}$$

Here, C signifies the three-system coupling degree, and the level range is from 0 to 1. R, U, and E symbolize the comprehensive level indexes of the rural revitalization, the new-type urbanization and the ecological environment, respectively. A larger value of C indicates a stronger degree of interaction and mutual influence among the three, and when C = 1, it indicates that the two systems are in an optimal coupling state. D is the degree of coupling coordination, which takes the value [0,1]. T represents the comprehensive evaluation index of rural revitalization, new-type urbanization and ecological environment. α, β, γ are weight coefficients and satisfy α + β + γ = 1. Referring to the related literature, with the same degree of importance, they all take the value of 1/3. According to the research of existing scholars (Jiang and Hu, 2021), the coordination hierarchy is divided into 10 stages (Table 2).

4.3.3 Dagum Gini coefficient

The Dagum Gini coefficient is a modification and improvement of the traditional Gini coefficient, which is widely used in the study of socio-economic issues, especially for measuring inequality. This paper applies the methodology to the analysis of overall, inter-regional, and intra-regional differences in the degree of coupled coordination and the sources of contribution to the differences (Equation 9; Dagum, 1997).

$$\text{Overall Gini coefficient: } G = \frac{\sum_{j=1}^{k}\sum_{h=1}^{k}\sum_{i=1}^{n_j}\sum_{r=1}^{n_k}\left|d_{ji}-d_{hr}\right|}{2n^2\bar{d}} \tag{9}$$

Here, n is the number of provinces, k is for the 7 regions divided, d_{ji} (d_{hr}) is the coordination degree of the R-U-E complex system of i(r) province in j (h) region, $\bar{d}$ is the average coordination degree of the R-U-E complex system in all areas, nj (nh) is the number of provinces in j (h) region. G is overall Gini coefficient, The Gini coefficient is decomposed into intraregional gap Ga, inter-regional gap Gb and hypervariable density Gc (Equations 10–13).

$$G = G_a + G_b + G_c \tag{10}$$

$$G_a = \sum_{j=1}^{k} G_{jj} P_j s_j \tag{11}$$

$$G_b = \sum_{j=2}^{k}\sum_{h}^{j-1} G_{jh}\left(p_j s_h + p_h s_j\right) D_{jh} \tag{12}$$

$$G_c = \sum_{j=2}^{k}\sum_{h}^{j-1} G_{jh}\left(p_j s_h + p_h s_j\right)\left(1 - D_{jh}\right) \tag{13}$$

Here, G_{jj} indicates intraregional variations; G_{jh} denotes differences between regions j and h, $p_j = \frac{n_j}{n}$, $s_j = \frac{n_j \bar{d}_j}{n\bar{d}}$, D_{jh} is the relative influence of the degree of coupling between regions j and h.

4.3.4 Kernel density estimation

The kernel density estimation method is used to analyze the dynamic evolutionary trend of the coupling coordination degree (Equation 14).

$$f(d) = \frac{1}{nh}\sum_{i=1}^{n} K\left(\frac{d-\bar{d}}{h}\right) \tag{14}$$

Here, n indicates the number of samples, d denotes the degree of coupling coordination, $\bar{d}$ denotes the average value of the coupling harmonization. K is kernel density function, h is bandwidth.

4.3.5 Spatial correlation analysis

The spatio-temporal pattern analysis mainly adopts the spatial autocorrelation method to explore the spatial distribution characteristics of the coupling and coordination of rural revitalization, new urbanization and ecological environment, and to test whether there exists spatial dependence, including the global spatial autocorrelation and local spatial autocorrelation index methods (Wang and Shi, 2022). Global spatial autocorrelation measures the degree of spatial correlation in the region, as measured by Moran's I index.

Local spatial autocorrelation is based on the global spatial autocorrelation and further analyzes the local correlation characteristics of each spatial element, the existence of statistical clustering or dispersion, and the determination of location (Li et al., 2020). A positive local Moran's I index is indicative of the proximity of similar types of areas and a negative value indicates proximity of dissimilar types of areas, with larger absolute values indicating greater proximity (Equation 15).

$$I = \frac{\sum_{i=1}^{n}\sum_{j\neq 1}^{n} w_{ij}(x_i - \bar{x})(x_j - \bar{x})}{S^2 \sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}} \tag{15}$$

Here, $S^2 = \frac{1}{n}\sum_{i=1}^{n}(x_j - \bar{x})^2$, $\bar{x} = \sum_{i=1}^{n} x_i$, w_{ij} is the spatial weight matrix, I takes the value [−1,1]. Greater than 0 is a positive spatial correlation, less than 0 is a negative spatial correlation.

4.3.6 Spatial durbin model

Spatial econometrics considers that the value of an economic geographic phenomenon or an attribute in a spatial unit of an area is not only related to the characteristics of the area itself, but also to the same phenomenon or attribute in spatial units of neighboring areas (Zou et al., 2024; Zhang et al., 2024d). Commonly-used spatial regression models are the spatial error model (SEM) that includes the interaction effect of the error term and the spatial lag model (SLM) that includes the endogenous interaction effect of the dependent variable. However, neither of these models accounts for the spatial correlation between the explanatory variables. This paper uses the spatial Durbin model (SDM) proposed by Elhorst (Zou et al., 2024), which can effectively analyze interregional spillovers and is of a more general form, to verify the evolution of spatio-temporal patterns and spatial spillover effects of key factors on coupled coordination (Equation 16).

$$y_{it} = \alpha\sum_{j=1}^{n} w_{ij}y_{jt} + \beta x_{it} + \gamma\sum_{j=1}^{n} w_{ij}x_{it} + \delta_i + \theta_t + \varepsilon_{it} \tag{16}$$

Here, y_{it} is the dependent variable, x_{it} is the independent variable, i, j represent space units, t represent time, α represents the spatial lag coefficient of the dependent variable, β represents the estimated coefficients of the independent variables, γ represents the coefficient of spatial overflow of the independent variable, δ_i epresent the spatial effect, θ_t represents the time effect, ε_{it} represents the random perturbation term, w_{ij} represents the spatial weight matrix.

5 Result

5.1 Level of integrated development of the R-U-E system

This paper measures the combined development level of R-U-E for the country, as a whole, as well as for each of the provinces in the seven regions using comprehensive evaluation indicators. East China includes Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, and Shandong. Central China includes Hubei, Hunan and Henan. South China includes Guangdong, Guangxi and Hainan. North China includes Beijing, Tianjin, Hebei, Shanxi and Inner Mongolia. The Northeast region includes Liaoning, Jilin and Heilongjiang. The Northwest Region includes Shaanxi, Gansu, Qinghai, Ningxia and Xinjiang. The Southwest region includes Sichuan, Yunnan, Guizhou, Chongqing and Tibet.

5.1.1 Spatial and temporal evolution of rural revitalization

As shown in Figure 3, the level of China's rural revitalization is on a growing trend, with the mean value increasing from 0.379 in 2011 to 0.441 in 2022, a growth rate of 16.34%, indicating that China has optimized the structure of the agricultural industry, improved the comprehensive quality of farmers, further narrowed the gap between urban and rural incomes, and further improved the quality of life of farmers. This was accomplished while building a beautiful countryside, reforming agriculture and rural areas. The level of rural revitalization in the seven regions of Northeast, North China, Central China, South China, East China, Northwest China and Southwest China tends to be consistent, all exhibiting an increasing trend, but there are obvious regional imbalances and inequalities. The mean values of rural revitalization in East and North China are 0.460 and 0.440, higher than the national average. The average values of rural revitalization in the Northeast, South China, Central China, Northwest China and Southwest China are 0.349, 0.343, 0.389, 0.345 and 0.358, respectively—all lower than the national average. The growth rates in South China, Central China and Northeast China were higher than those in other regions, thus demonstrating that other regions must catch up in order to create narrow interregional differences. In 2022, the overall regional differences are shown as East China > Central China > North China > Northeast > South China > Southwest > Northwest.

As shown in Figure 4, The levels of rural revitalization during the study periods exhibited an increasing trend, except for Beijing, Hebei, Shaanxi, Qinghai and Tibet, which showed a slight decrease. The top five growth rates were in Guangdong (51.96%), Hubei (47.5%), Heilongjiang (38.43%), Zhejiang (37.88%) and Fujian (33.59%). In terms of average value, the top five provinces were Zhejiang (0.555), Shanghai (0.550), Tianjin (0.529), Tibet (0.504) and Beijing (0.494), all of which were higher than the national average. These provinces have developed special industries based on local resource endowments and market demand, diversified their rural economic industries and achieved a high level of rural revitalization, and although Tibet's economic foundation is weak, it has made significant progress in terms of ecological livability and rural governance. Ranking in the bottom five are Yunnan (0.292), Chongqing (0.313), Gansu (0.314), Guangxi (0.318) and Hainan (0.320), all of which are lower than the national average. These provinces have a larger number of poor areas, traditional methods of agricultural production and operation, and the level of rural revitalization has not been raised significantly. As of 2022, the overall level of rural revitalization is low, with only Shanghai, Tianjin, Zhejiang, Hubei, Fujian, Shandong and Guangdong having a composite index of more than 0.5, while all other provinces are below 0.5.

5.1.2 Spatial and temporal evolution of new-type urbanization

As shown in Figure 5, China's new-type urbanization level has significantly improved, growing from 0.417 in 2011 to 0.456 in 2022, a growth rate of 10.01%. East China, North China, Central China, South China, Northwest China and Southwest China all exhibited a growing trend in the level of new urbanization, with growth rates of 8.91%, 3.11%, 17.18%, 10.50%, 14.21% and 14.14%, respectively, thus indicating that all regions are actively exploring the mode of new urbanization and maintaining rapid economic growth, with

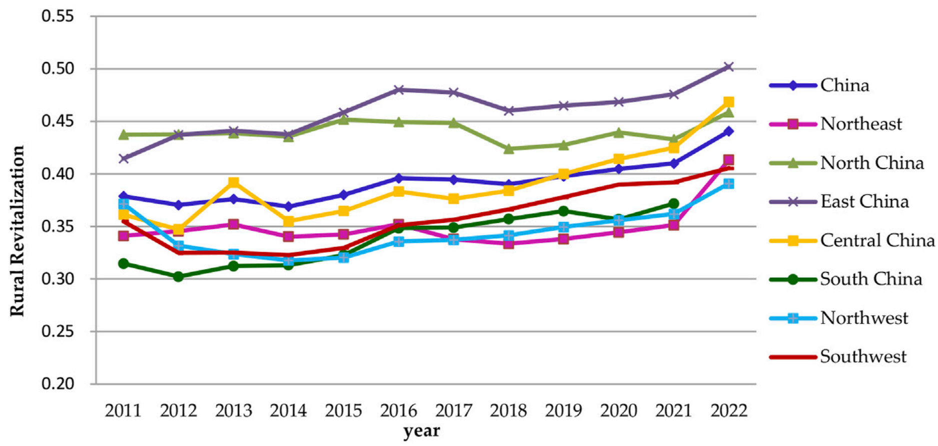

FIGURE 3
Comprehensive evaluation index of Rural Revitalization.

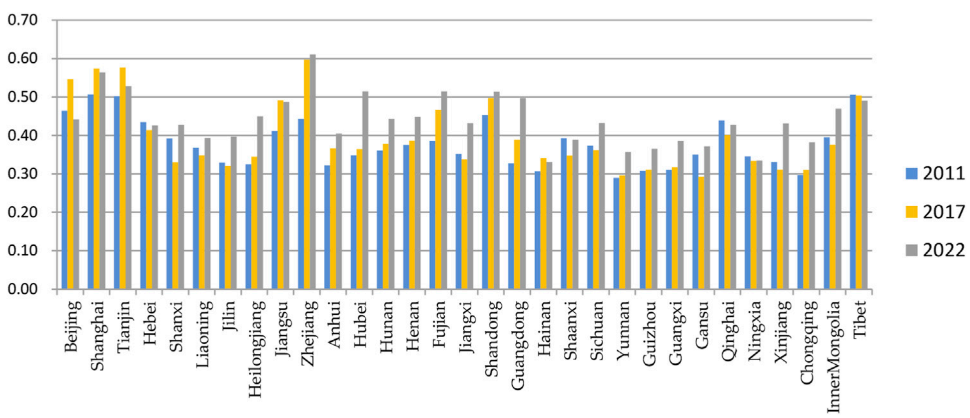

FIGURE 4
Level of rural revitalization by province, 2011, 2017, 2022.

populations clustering in cities and towns, and the spatial scope constantly expanding with infrastructure and public services. Significant progress has been made in the level of new urbanization. There was a slight decline of 1.63% in the northeastern region, where policies should be further strengthened to promote the new urbanization process. In terms of mean values, East China (0.535), North China (0.455) and Central China (0.446) are higher than the national average, while South China (0.421), Northeast China (0.381), Southwest China (0.375) and Northwest China (0.368) are lower than the national average, indicating that there are differences in the levels of new urbanization in China's regions and that there is an imbalance in regional development. In 2022, the regional differences show East China > Central China > North China > South China > Northeast > Northwest > Southwest.

All provinces (Figure 6), except for Beijing, Shanghai, Tianjin, Liaoning and Jilin, which had a slight decline, exhibited a general growth trend. The top growth rates were in Guangxi (30.06%), Ningxia (29.86%), Hunan (25.48%), Anhui (23.45%) and Guizhou (22.28%) provinces. The top five averages include Shanghai (0.763), Beijing (0.597), Guangdong (0.551), Zhejiang (0.549) and Jiangsu (0.546), all of which were higher than the national average. These provinces are economically active, highly open, innovative, densely populated and have significant urbanization. The bottom five are Tibet (0.321), Qinghai (0.331), Gansu (0.342), Guangxi (0.346) and Jilin (0.355), all lower than the national average. These provinces are in inland areas, where geographical advantages are more scarce, the economic foundation is weak, the population size is small, and the effects of urbanization are not apparent.

5.1.3 Spatial and temporal evolution of ecosystems

As shown in Figure 7, the national ecological level shows a steady growth trend from 0.418 in 2011 to 0.445 in 2022, an increase of 6.36%. All parts of the country are actively putting into practice the concept of "green mountains and green water are golden mountains and silver mountains," making continuous improvement in and optimization of the ecological environment a key indicator of people's wellbeing, and the level of the ecological environment has been significantly upgraded. All seven regions, with the

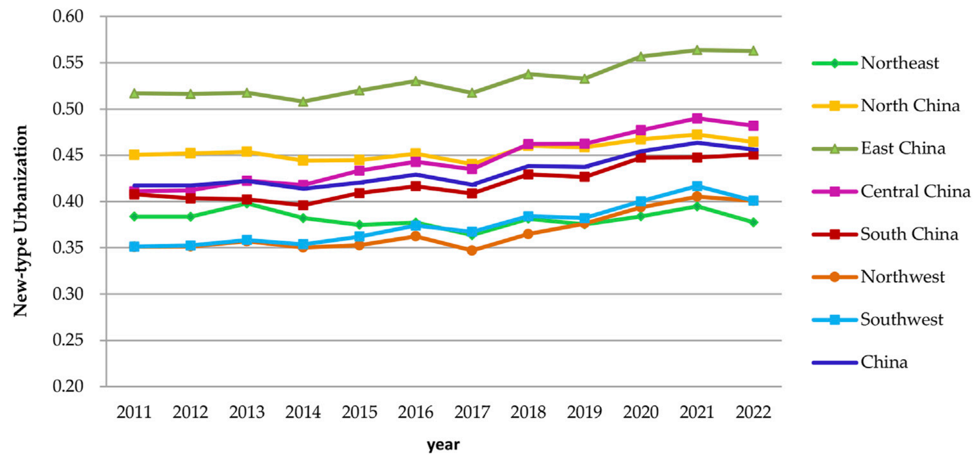

FIGURE 5
Comprehensive evaluation index of New-type Urbanization.

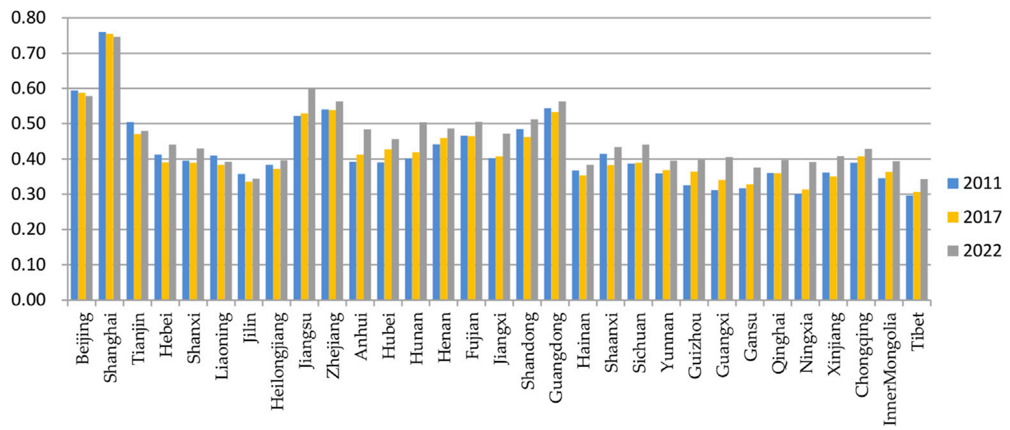

FIGURE 6
Level of New-type Urbanization by province, 2011, 2017, 2022.

exception of South China and Southwest China, which are on a downward trend, are on an upward trend, however there is an imbalance. In terms of ecological averages, Northeast (0.440), North (0.439), Central (0.441), South (0.531) and Southwest China (0.439) are above the national average, while East and Northwest China are below the national average. The level of ecological environment in South China is generally smoother and higher than in other regions. The northwestern region grew faster, at a rate of 25.44%, which means other regions must "play catch up" to gradually narrow the regional gap. In 2022, regional differences are generally characterized by South China > North China > Northeast China > Central China > Southwest China > East China > Northwest China.

All provinces (Figure 8), The top growth rates were in Beijing (41.86%), Ningxia (41.25%), Xinjiang (30.78%), Gansu (24.49%) and Heilongjiang (23.54%) provinces. In terms of the average values, the top five provinces, Guangdong (0.593), Beijing (0.546), Hainan (0.511), Yunnan (0.498), Guangxi (0.490), are higher than the national average. Guangdong and Beijing are among the economically developed cities, and their urban ecological environmental governance has sufficient material basis. Hainan, Yunnan and Guangxi have a strong natural resource base, high ecological coverage, and are actively involved in ecological governance, with a high level of ecological environment. The bottom five are Qinghai (0.243), Tianjin (0.272), Shanghai (0.319), Xinjiang (0.322) and Tibet (0.369), all lower than the national average. Tianjin and Shanghai have put a certain amount of pressure on the environment in the course of their economic development. Meanwhile, Qinghai, Tibet and Xinjiang have unique advantages in terms of natural resources, but the effectiveness of environmental governance needs to be improved.

5.2 Spatial and temporal evolution of coupled coordination

In this paper, the coupling coordination model is used to measure the coupling coordination degree of the R-U-E system,

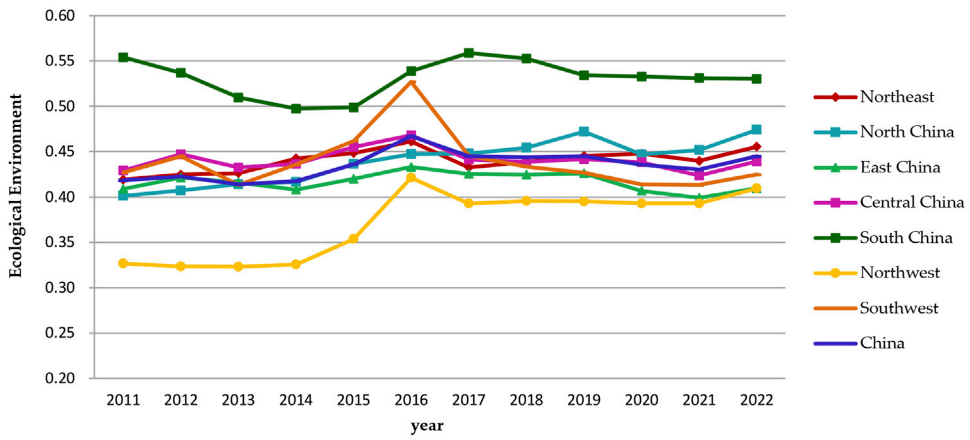

FIGURE 7
Comprehensive evaluation index of Ecological Environment.

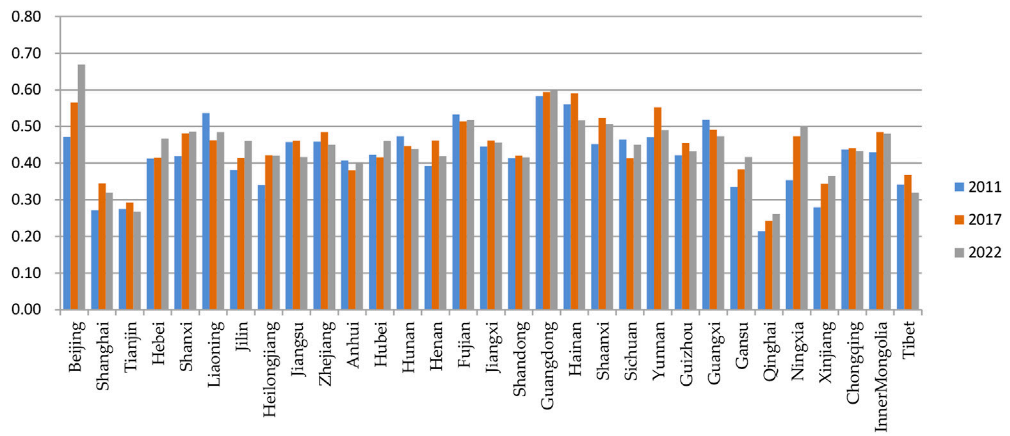

FIGURE 8
Level of Ecological Environment by province, 2011, 2017, 2022.

and to determine the spatio-temporal evolution and characteristics of the national and seven regionals coupling coordination.

As shown in Table 3, From 2011 to 2022, the national R-U-E coupled coordination index shows a growing trend from 0.545 (barely coordinated) to 0.643 (primary coordination), with a growth rate of 18.04%, indicating that China's coordinated urban-rural development and the harmonious coexistence of humans and nature have achieved remarkable results, but the index still falls within the range [0.5–0.7] and is, thus, between the stages of barely coordinated and primary coordination. Therefore, much room for improvement exists. This type of coupled coordination requires two phases. The period from 2011 to 2020 is the stage of barely coordinated urbanization, which was the transition period between traditional urbanization, which unilaterally pursues economic growth and spatial expansion, and the new type of people-centered urbanization. However, environmental damage and waste of resources brought about by the crude development model continued to persist. The period 2020–2022 was the primary coordination phase, in which the concepts of integrated urban and rural development and ecological civilization were been brought to unprecedented, high levels, the quality of urbanization had been improved, construction in and development of the countryside had made remarkable achievements, the ecological environment had been further optimized, and the level of coordination had increased. In terms of provinces, except for Tianjin and Liaoning, which show a decreasing trend, all other provinces show a growing trend. The top five growth rates are Ningxia (54.02%), Guangxi (43.91%), Qinghai (41.06%), Xinjiang (39.9%), and Guizhou (34.2%), which indicates that the state of coordination is positively improving. The structure of coupled coordination is continuously optimized, with the proportion of provinces with high coordination types gradually increasing and provinces with dysfunctional types gradually disappearing. The top five provinces in terms of the mean value of the coupling coordination index were Beijing (0.806), Zhejiang (0.778), Shanghai (0.750), Guangdong (0.733) and Jiangsu (0.729), which are socio-economically developed, densely populated and geographically advantageous regions. These areas have achieved remarkable results in the coordinated development of R-U-E by actively

TABLE 3 The R-U-E system coupling coordination degree of China.

Area	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Beijing	0.761	0.757	0.742	0.756	0.799	0.824	0.840	0.850	0.871	0.831	0.825	0.812
Shanghai	0.669	0.738	0.744	0.740	0.753	0.772	0.784	0.753	0.771	0.756	0.764	0.753
Tianjin	0.590	0.605	0.590	0.576	0.589	0.596	0.622	0.568	0.568	0.573	0.574	0.579
Hebei	0.613	0.609	0.658	0.641	0.630	0.612	0.584	0.611	0.611	0.633	0.632	0.655
Shanxi	0.577	0.548	0.566	0.547	0.563	0.572	0.544	0.563	0.572	0.595	0.608	0.655
Liaoning	0.615	0.620	0.619	0.591	0.562	0.575	0.551	0.564	0.566	0.575	0.588	0.600
Jilin	0.473	0.467	0.494	0.479	0.494	0.486	0.449	0.468	0.473	0.487	0.508	0.537
Heilongjiang	0.474	0.498	0.532	0.525	0.531	0.570	0.520	0.536	0.530	0.553	0.559	0.611
Jiangsu	0.688	0.719	0.721	0.702	0.771	0.768	0.741	0.735	0.722	0.715	0.719	0.747
Zhejiang	0.718	0.757	0.753	0.748	0.721	0.808	0.803	0.820	0.808	0.799	0.799	0.803
Anhui	0.510	0.489	0.504	0.489	0.542	0.554	0.553	0.566	0.578	0.602	0.601	0.637
Hubei	0.542	0.547	0.628	0.565	0.599	0.619	0.580	0.611	0.635	0.658	0.675	0.707
Hunan	0.580	0.571	0.574	0.574	0.591	0.620	0.598	0.61	0.622	0.655	0.667	0.690
Henan	0.586	0.579	0.595	0.580	0.609	0.641	0.638	0.661	0.665	0.655	0.646	0.674
Fujian	0.667	0.660	0.664	0.653	0.700	0.704	0.712	0.720	0.723	0.749	0.733	0.763
Jiangsu	0.563	0.554	0.546	0.503	0.525	0.571	0.561	0.577	0.588	0.611	0.624	0.673
Shandong	0.673	0.685	0.685	0.684	0.694	0.712	0.685	0.687	0.684	0.688	0.695	0.719
Guangdong	0.665	0.694	0.695	0.679	0.709	0.736	0.728	0.746	0.761	0.78	0.786	0.817
Hainan	0.516	0.446	0.452	0.447	0.472	0.531	0.545	0.574	0.556	0.533	0.539	0.550
Shaanxi	0.608	0.567	0.572	0.555	0.549	0.569	0.569	0.593	0.603	0.612	0.625	0.640
Sichuan	0.574	0.577	0.557	0.542	0.558	0.577	0.548	0.578	0.593	0.621	0.630	0.651
Yunnan	0.457	0.305	0.376	0.375	0.404	0.496	0.499	0.519	0.518	0.536	0.541	0.578
Guizhou	0.421	0.334	0.353	0.370	0.445	0.490	0.489	0.496	0.509	0.546	0.541	0.565
Guangxi	0.419	0.371	0.400	0.401	0.423	0.480	0.478	0.508	0.506	0.533	0.563	0.603
Gansu	0.406	0.379	0.384	0.383	0.415	0.436	0.394	0.424	0.443	0.479	0.507	0.543
Qinghai	0.341	0.342	0.278	0.308	0.310	0.527	0.409	0.432	0.456	0.479	0.489	0.481
Ningxia	0.361	0.324	0.352	0.333	0.374	0.449	0.435	0.472	0.495	0.514	0.531	0.556
Xinjiang	0.416	0.384	0.391	0.370	0.359	0.440	0.430	0.469	0.494	0.504	0.517	0.582
Chongqing	0.487	0.476	0.463	0.445	0.459	0.522	0.521	0.529	0.562	0.575	0.579	0.602
Inner	0.526	0.553	0.549	0.541	0.555	0.580	0.558	0.576	0.585	0.599	0.601	0.644
Tibet	0.391	0.352	0.437	0.476	0.509	0.598	0.456	0.483	0.444	0.477	0.579	0.507

implementing the strategies of new-type urbanization and rural revitalization, and adhering to the priority of improving the environment. In the bottom five are Qinghai (0.404), Gansu (0.432), Ningxia (0.433), Xinjiang (0.446) and Guizhou (0.463), which are rich in resources but economically underdeveloped, with poor transportation infrastructure, a lack of openness to the outside world and a poor level of coordination. In terms of coordination, as of 2022, no city has achieved quality coordination, and the provinces with good coordination are Beijing, Guangdong and Zhejiang, accounting for 6.45%; Shanghai, Jiangsu, Hubei, Fujian and Shandong are intermediate level coordination, accounting for 16.13%; Shanxi, Liaoning, Heilongjiang, Anhui, Hunan, Henan, Jiangxi, Shanxi, Sichuan, Guangxi, Chongqing and Inner Mongolia for primary coordination, accounting for 38.71%, Jilin, Hainan, Yunnan, Guizhou, Gansu, Ningxia, Xinjiang and Tibet are barely harmonized, accounting for 25.81%, Qinghai for endangered disorders. The coupling coordination of all provinces shows a positive trend, but differences are still evident.

The level of coupling coordination in all regions showed an upward trend, but with significant differences and fluctuations

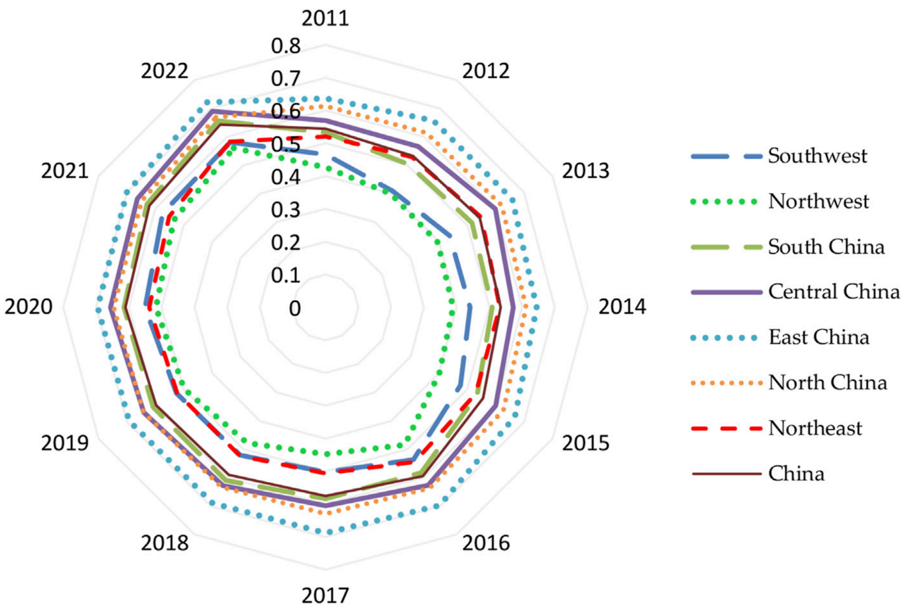

FIGURE 9
Trends in national and seven regional coupling harmonization.

(Figure 9). Seven regionals growth rates from high to low for the Northwest (31.43%), Southwest (24.59%), South China (23.12%), Central China (21.25%), East China (13.37%), Northeast China (11.91%) and North China (9.06%). Southwest China and South China to the other regions to catch up with the effect is obvious. The unchanged character of coordination in Northeast and North China as barely coordinated and primary. Northwest and Southwest China evolved from near-disorder to barely coordinated, South and Central China evolved from barely coordinated to primary coordinated, and East China evolved from primary coordinated to intermediate coordinated. In terms of averages, North China (0.633), East China (0.679) and Central China (0.618) were higher than the national average, while Northeast China (0.536), South China (0.573), Northwest China (0.461) and Southwest China (0.502) were lower than the national average. In 2022, regional differences generally show East China > South China > Central China > North China > Northeast > Northwest, with Central China catching up with North China in 2021.

5.3 Regional spatial differences and decomposition

The Dagum Gini coefficient is applied to provide a detailed breakdown of the regional variability and sources of the coupled coordination of the R-U-E system in 2011–2022 and to further explore the causes of the spatial disequilibrium.

5.3.1 Evolution of national and intra-regional disparities

As shown in Figure 10, The national Gini coefficient peaked at 0.145 in 2012, and then maintained a decreasing trend, with a Gini coefficient of 0.078 in 2022. This was a decrease of 32.17%, indicating that the differences in the coupled and coordinated development of the three systems of China's R-U-E have gradually narrowed, and the trend of coordinated development has become obvious. However, the Gini coefficient was still higher than 0.05 in 2022, and it will be necessary to increase efforts to narrow the gap further. There is a fluctuating downward trend within each region, with South China, North China, East China, Central China, Southwest China, Northwest China, Northwest China, and Northeast China experiencing a decline rate of 12.62%, 13.64%, 28.53%, 35.29%, 39.19%, 54.05%, and 54.10%, respectively, from 2011 to 2022. The spatial imbalances in the level of coupled coordination among the seven regions have all improved, with the implementation of coordinated development strategies, such as the revitalization of the old industrial zones in the northeast, the prioritization of development in the east, the rise of central China, and the development of the western region, leading to a continued narrowing of intra-regional disparities and weakening of spatial imbalances. In terms of the degree of difference, from 2011 to 2022, the average value of the Gini coefficient in South China was 0.104, which exhibited the largest intra-regional difference and obvious unbalanced coordinated development. Guangdong is a province that opened earlier and boasts a developed economy, a high level of urbanization and large reserves of human and material capital for rural revitalization and ecological improvement. It has an innate advantage in coupled and coordinated development, while Guangxi and Hainan, on the other hand, are in the exploratory stage of coupling and coordination, and there is a big gap between them and Guangdong. The Gini coefficients of the remaining six provinces showed Northwest (0.079) > North China (0.069) > East China (0.066) > Southwest (0.061) > Northeast (0.043) > Central China (0.012). Central China has the smallest regional differences, indicating that all provinces are supported by the

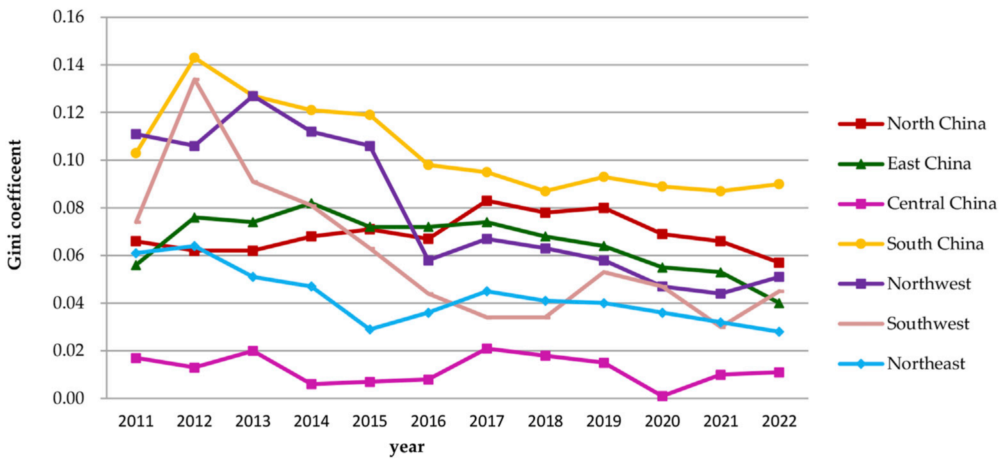

FIGURE 10
Trends in the evolution of the Dagum Gini coefficient in the region.

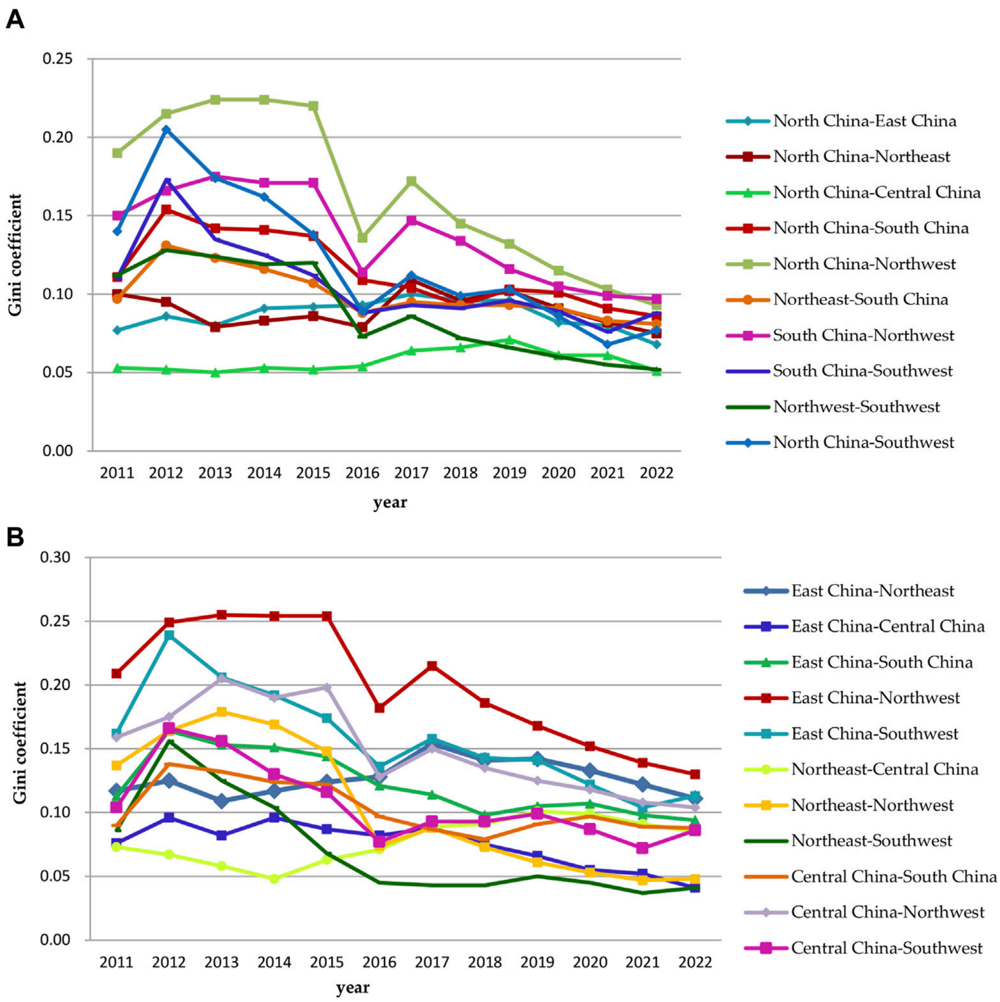

FIGURE 11
(A) Trends in the evolution of the Dagum Gini coefficient between regions. **(B)** Trends in the evolution of the Dagum Gini coefficient between regions.

corresponding policies, and therefore the level of coupled and coordinated development is relatively balanced across provinces.

5.3.2 Evolution of differences between regions

As shown in Figures 11A, B, the Gini coefficient of the Northeast-Central China region is on an upward trend, from 0.073 in 2011 to 0.085 in 2022, with an increase of 16.44%, indicating that the differences between regions are on a widening trend. All other interregional Gini coefficients showed a downward trend, with the gap between regions gradually decreasing. East China-Northwest China and North China-Northwest China exhibit the largest degrees of difference. Between these regions, the average value of the coefficient was 0.199 and 0.164, respectively, during the study period and are exhibiting a rapid downward trend, down 37.8% and 51.05%. This indicates that the Northwest China's development of kinetic energy is strong, the catching-up effect is obvious, and the coupling and coordination level differences between East China and North China is rapidly shrinking; and North China is catching up with Northwest China more rapidly than East China is. The average values of Gini coefficients between North China and other regions are, in descending order, North China-Southwest (0.121), North China-South China (0.114), North China-Northeast China (0.090), North China-East China (0.087) and North China-Central China (0.057). During the study period, Southwest China, South China, and Northeast China rapidly narrowed the gap with North China, with growth rates of 45%, 25%, and 22.52%, respectively. East China gradually and steadily moved closer to North China, with a growth rate of 11.69%; and Central China slowly narrowed the gap with North China with a growth rate of 3.77%. The average Gini coefficients of East China and other regions are in the order of East China-Southwest (0.158), East China-Northeast (0.127), East China-South China (0.122), and East China-Central China (0.075), with Central China catching up with East China by 46.05% growth, Southwest approaching East China by 30.25% growth, and South China narrowing the gap with East China by 16.81% growth, and East China by 5.13% growth. Northeast is slowly approaching East China with a growth rate of 5.13%. The Gini coefficients of the Northeast and other regions are not very different from each other, in the order of Northeast-Northwest (0.103), Northeast-South China (0.100), Northeast-Central China (0.078) and Northeast-Southwest (0.070), Northwest and Southwest are rapidly narrowing the gap with the Northeast with the magnitude of 64.96% and 52.33%, respectively, and Central and South China with the speed of 16.49% and 16.44%, respectively. Gradually approaching with the Northeast. The average values of Gini coefficients between Central China and other regions are in the order of Central China-northwestern (0.150), central China-Southwestern (0.107), and Central China -Southern (0.103), with Northwestern, Southwestern, and Southern narrowing the gap with Central China at a rate of 34.59%, 17.31%, and 2.22%, respectively. The Gini coefficients for South China-Northwest and South China-Southwest are 0.137 and 0.106 and equalize by 35.33% and 20% respectively. The Northwest-Southwest Gini coefficient is 0.089, with the Southwest moving rapidly closer to the Northwest by 53.57%. The above results indicate that the adoption of reasonable policies by the relevant regions has contributed to the narrowing of the coordinated development gap among the seven regions and that the level of coupled coordination is shifting from regionally-unbalanced development to relatively-balanced regional development.

5.3.3 Sources and contributions of regional variations

In this paper, the Dagum Gini coefficient decomposition is used to reveal the sources of regional differences in coupled coordination and the trends in their contributions (Table 4). Interregional differences contribute the most to the overall differences, with an average value of 72.84% from 2011 to 2022, and fluctuations between 70.22% and 76.35%, suggesting that inter-regional differences are the main cause of the overall differences in China's R-U-E coupled and coordinated development. Intra-regional differences contributed the least, with a mean value of 9.44%, fluctuating between 9.22% and 9.89%, indicating that intra-regional differences had the least impact on coupled and coordinated development.

The contribution of hypervariable density to the overall variance is in the range of 14.73%–19.96%, with a mean value of 17.72%, indicating that the problem of inter-regional crossover has a certain impact on the coordination of R-U-E coupling in China. The trend shows a fluctuating downward trend in intra-regional variation, from 9.46% in 2011 to 9.31% in 2022, with a decreasing of 1.59%.The inter-regional differences exhibit an inverted, U-shaped trend of increasing and then decreasing, with the highest point in 2015 and a decrease of 1.10% in 2022 compared to 2011, and the hypervariable density exhibits a U-shaped trend of decreasing and then increasing from 19.01% in 2011 to 19.96% in 2022, with an increase of 4.76%. The hypervariable density exhibits a "U" trend of decreasing and then increasing values, from 19.01% in 2011 to 19.96% in 2022, with an increase of 4.76%. The overall change in the rates of contribution in the three categories of variances is not significant. While interregional differences are the main factor influencing the overall variance, their impact is gradually diminishing. Therefore, to reduce the overall differences in the level of coordination of rural revitalization, new urbanization and ecological environment coupling, we should focus on inter-regional differences, paying particular attention to the specificity of the coupled and coordinated development of each province, but also to the overall coordination of inter-regional development.

5.3.4 Characterization of the evolution of regional disparities

Six years of the study period 2011, 2014, 2017, 2019 and 2022 were selected to use in the kernel density plots of the coupled coordination degree in China and within the seven regions, and to analyze the evolutionary trends and characteristics of the coupled coordination differences in R-U-E in China (Figure 12).

From the changes in the degree of coupling coordination, the center of the kernel density curves for the whole country and the Northeast, North, South, Central, Southwest, and Northwest regions shifted to the right to varying degrees, with the increase in the number of years indicating that the level of coupled and coordinated development of the R-U-E system in the whole country and in each region continues toward optimization. East China exhibits a

TABLE 4 Dagum Gini coefficient and its decomposition.

Year	Overall difference	Intra-regional difference		Nterregional difference		Hypervariable density	
		Contribution value	Contribution	Contribution value	Contribution	Contribution value	Contribution
2011	0.115	0.011	9.46%	0.082	71.53%	0.022	19.01%
2012	0.145	0.013	9.25%	0.106	73.23%	0.025	17.52%
2013	0.136	0.013	9.22%	0.102	74.89%	0.022	15.90%
2014	0.133	0.013	9.40%	0.099	74.00%	0.022	16.60%
2015	0.127	0.011	8.92%	0.097	76.35%	0.019	14.73%
2016	0.098	0.010	9.89%	0.071	72.31%	0.018	17.80%
2017	0.112	0.011	9.37%	0.085	75.90%	0.017	14.73%
2018	0.101	0.010	9.62%	0.074	73.23%	0.017	17.15%
2019	0.100	0.010	9.92%	0.070	70.22%	0.020	19.87%
2020	0.090	0.008	9.36%	0.064	71.14%	0.017	19.50%
2021	0.081	0.008	9.58%	0.057	70.50%	0.016	19.93%
2022	0.078	0.007	9.31%	0.055	70.74%	0.016	19.96%

rightward and then leftward trend, indicating that the level of coupling coordination tended to increase and then decrease.

In terms of distribution and trends, the distribution of nuclear density curves in the seven regions exhibits different characteristics. The height of the main peaks in the country as a whole, in the northeastern, northern, eastern and southwestern regions, has been increasing year by year, with a tendency for the width to shrink. The phenomenon of a “single peak” has always been present, indicating that the degree of coordination of coupling at the overall level has been concentrated year by year, and that there is no polarization. The decreasing height of the main peak in South China and the insignificant change in width indicate that there is a decreasing trend in the absolute internal differences. The height of the main peak in Central China reached its highest point in 2014, at which point, the width is at its narrowest. After 2014, the height exhibited a trend of decreasing and then increasing, and the width narrowed year by year, which indicates that the degree of concentration in Central China was the most significant in 2014. The regional difference exhibited a widening trend in 2014–2017, and the degree of concentration became gradually more obvious in 2017–2022. The height of the main peak in Southwest reached its highest point in 2017, at which point, the width is at its narrowest, which indicates that the degree of concentration in Central China was the most significant in 2017. The height of the main peak decreases, the width grows, and regional differences increase in 2017–2019. From 2019–2022, there is significant main peak height growth, width narrowing, and coupling coordination concentrating from year to year.

In terms of distributional extensibility, there is a significant right trailing phenomenon in North China, i.e., there are some provinces within the region that experienced significantly higher coupling coordination than other provinces within the same region. There is a trailing phenomenon in the Northwest in 2011–2019, after which the trailing disappears, which indicates that the level of coordinated development in the Northwest became more balanced. There is no trailing phenomenon in other areas.

5.4 Spatial correlation

5.4.1 Global correlation

The global Moran’s I index was used to test whether there is spatial correlation in the coupled coordination of R-U-E in China (Table 5). The global Moran’s I index is greater than 0, its correlation attribute is positive, and it is significant at the 1% level for the 2011–2022 time period, indicating that there is a spatial spillover effect in the level of coupling coordination, and that the level of coupling coordination among neighboring provinces influences each other. The index exhibits a fluctuating downward trend in the 0.148–0.105 range, indicating that the spatial correlation was gradually weakening.

5.4.2 Local correlation

In order to analyze the degree of local agglomeration of R-U-E coupling coordination in a more detailed manner, this paper takes 2011, 2017 and 2022 as the time nodes, and combines the quadrant changes of Moran’s I index to count the distributions of 31 provinces in the four types, namely, high-high, low-high, low-low, and high-low. The scatter plots are shown in Figure 13. The results are shown in Table 6. The coupling coordination of the R-U-E system in each province is mainly clustered in the high-high and low-low regions, indicating that the clustering effect occurs in regions with higher coupling coordination, as well as regions with lower coupling coordination. High-high agglomeration indicates a positive correlation between the region and its neighboring regions, most of which are located in East, North and Central China. Shanghai, Hebei, Shanxi, Jiangsu, Zhejiang, Hunan, Henan, Fujian and Shandong have long been in the first quadrant, with higher levels

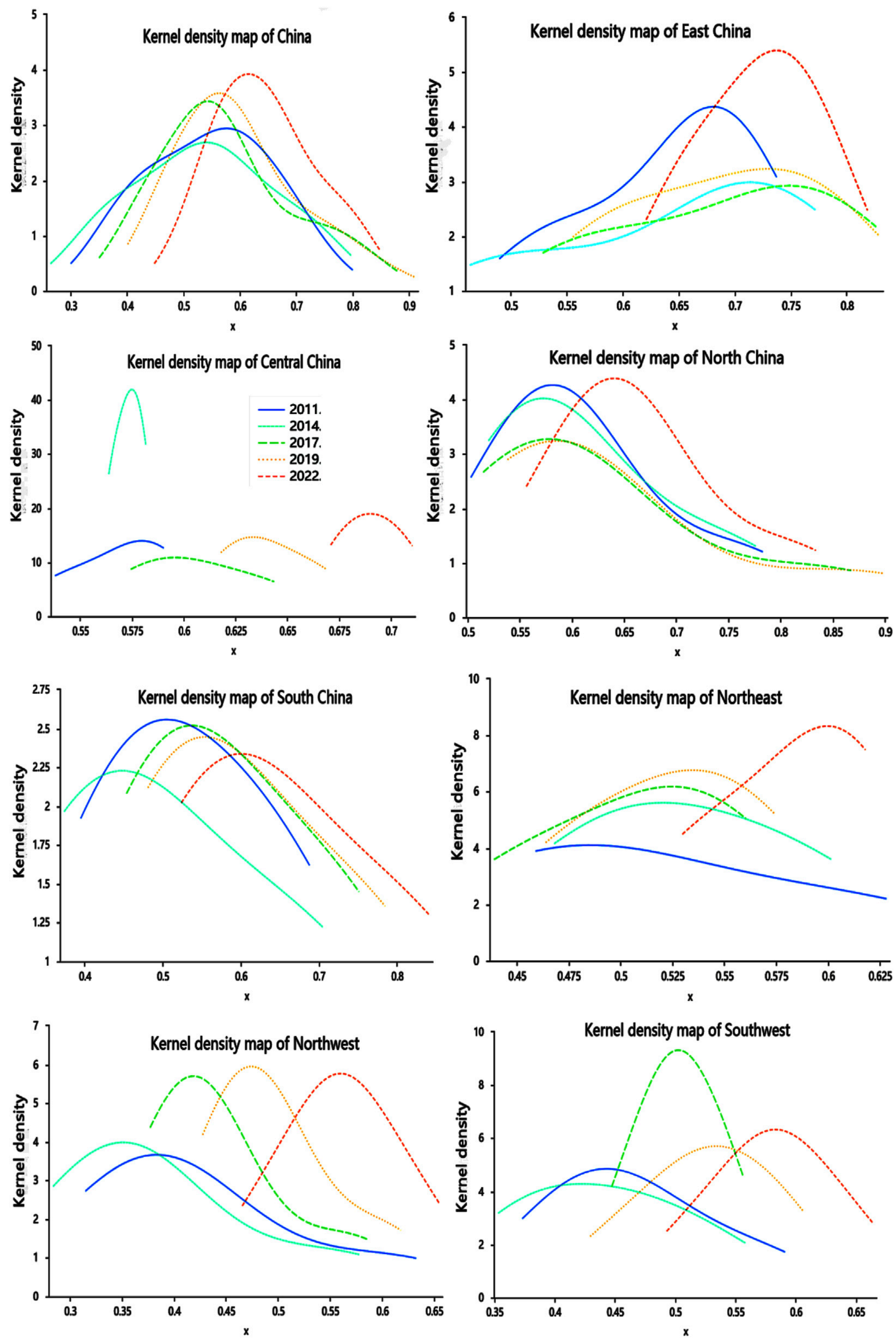

FIGURE 12
Trend plot of kernel density for R-U-E coupling coordination.

of economic development, faster urbanization, leading rural modernization and development, stronger ecological and environmental governance, and good regional linkages, leading to agglomeration in these areas of higher coupling coordination. Although Beijing and Tianjin exhibit high levels of coupled coordination, their spatial spillovers to neighboring provinces

TABLE 5 Moran's I index in China.

Year	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Moran's Index	0.148	0.158	0.171	0.160	0.153	0.115	0.155	0.126	0.113	0.112	0.102	0.105
Z	5.171	5.449	5.827	5.516	5.340	4.269	5.408	4.592	4.24	4.176	3.896	3.946
P	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.002	0.001	0.002	0.000	0.001

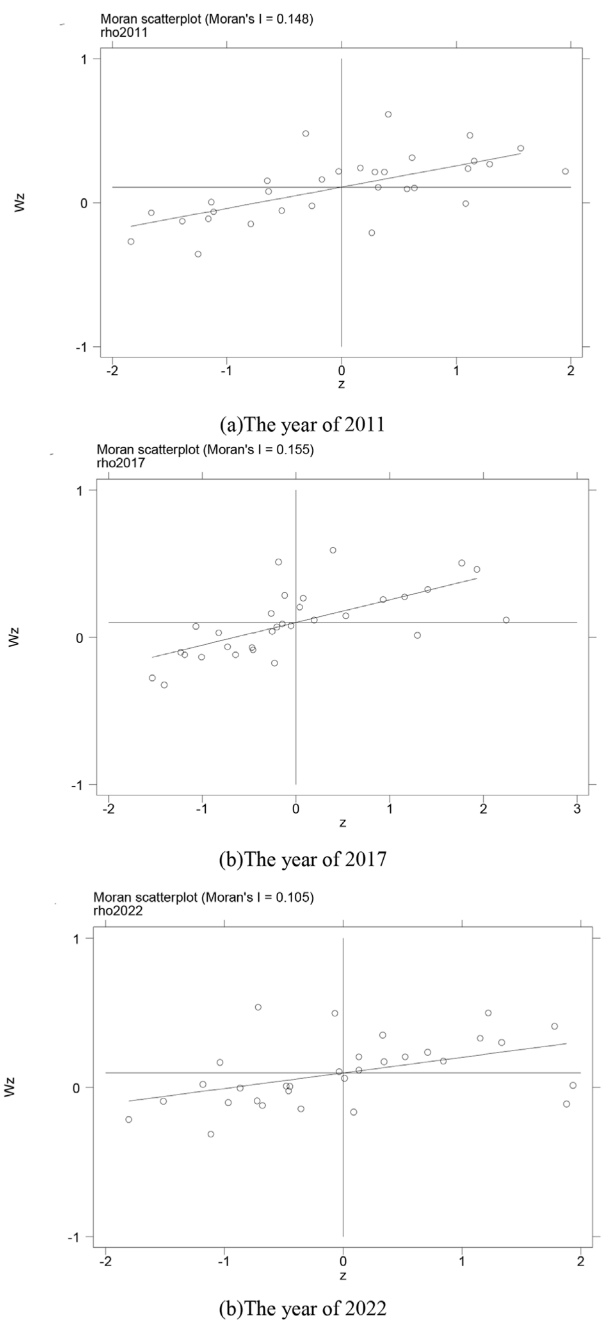

FIGURE 13
The R-U-E system coupling coordination localized Moran scatterplot.

decline, and became low-high and high-low type regions, respectively, in 2022. Most of the low-low agglomeration areas are in the southwestern region, with Yunnan, Guizhou, Gansu, Qinghai, Ningxia, Xinjiang, Chongqing and Tibet located in the third quadrant for a long period of time. These areas have relatively weak economic bases, low levels of urbanization, a relatively backward countryside, and are not developing in a coordinated manner with each other, which resulted in a low degree of coupling coordination. The low-high agglomeration area is unstable in all provinces except Anhui and Guangxi, indicating that such provinces have a high degree of coupling and coordination with neighboring provinces, but a low degree of coupling and coordination with themselves. The lowest number of high-low provinces indicates a high degree of coordination in its own coupling and a low degree of coordination among neighboring provinces.

5.5 Spatial effects analysis

5.5.1 Selection of variables

Rural revitalization, new-type urbanization and ecological environment are a unity of mutual influence and interdependence, and the level of their coupled and coordinated development is affected by a variety of factors. This paper, based on the analysis of the influencing mechanism, draws on the research results of relevant scholars (Zhang J. Y. et al., 2023; Lu, 2021; Zhou and Guo, 2024; Xu W. X. et al., 2019; Wang and Xu, 2023; Zhang et al., 2024e) and combines the characteristics of the whole country and the seven regions, selects the relevant explanatory variables, and explores the extent of their influence on the coupling and the degree of coordination. These include:

(1) Level of economic growth (gdp). The level of economic growth represents the financial strength of a region, which is the material basis for urban infrastructure construction and the provision of basic public services, rural industrial support, rural civilization construction and ecological livability, environmental protection and pollution control, etc. It is a key factor affecting the coordinated development of the R-U-E coupling and is expressed by *per capita* GDP.
(2) Innovation drive (tec). This is indicative of the level of science and technology, which is a primary productive force and plays an important driving role in promoting the integration of the three industries in the countryside, urban spatial planning, the realization of a circular economy, and the promotion of green and low-carbon

TABLE 6 Coupled coordination of spatially differentiated cluster segmentation.

Year	High-high	Low-high	Low-low	High-low
2011	Beijing, Shanghai, Tianjin, Hebei, Shanxi, Liaoning, Jiangsu, Zhejiang, Hunan, Henan, Fujian, Jiangxi, Shandong, Shaanxi	Jilin, Anhui, Hubei, Heilongjiang, Guangxi, Inner Mongolia	Hainan, Yunnan, Guizhou, Gansu, Qinghai, Ningxia, Xinjiang, Chongqing, Tibet	Guangdong, Sichuan
2017	Beijing, Shanghai, Tianjin, Hebei, Jiangsu, Zhejiang, Hubei, Hunan, Henan, Fujian, Shandong, Guangdong	Anhui, Shanxi, Liaoning, Jilin, Jiangxi, Hainan, Shaanxi, Guangxi, Inner Mongolia	Heilongjiang, Sichuan, Yunnan, Guizhou, Gansu, Qinghai, Ningxia, Xinjiang, Chongqing, Tibet	
2022	Shanghai, Hebei, Shanxi, Jiangsu, Zhejiang, Hubei, Hunan, Henan, Fujian, Jiangxi, Shandong, Guangdong, Inner Mongolia	Tianjin, Liaoning, Jilin, Anhui, Hainan, Shaanxi, Guangxi	Heilongjiang, Yunnan, Guizhou, Gansu, Qinghai, Ningxia, Xinjiang, Chongqing, Tibet	Beijing, Sichuan

development. It is expressed in terms of the number of patents and inventions *per capita* in the region.

(3) Openness to the outside world (open). Openness promotes circulation between provinces, between cities within provinces, and the free flow of production factors, such as technology and talent, promoting urban-rural integration and high-quality regional development. It is expressed as the ratio of foreign direct investment to GDP.

(4) Government intervention (gov). Rural revitalization and new urbanization are two major strategies implemented by the Chinese government to achieve common wealth. The concept of harmonious coexistence between humans and nature is present in both strategies, and government guidance is the catalyst to achieve R-U-E-coupled and coordinated development, which is expressed by using the share of local fiscal expenditure in GDP.

(5) Human capital level (capi). The realization of urban modernization requires the participation of highly-qualified and skilled personnel. The revitalization of talent is a major component of rural revitalization and an important factor in realizing the rise of the countryside, as expressed by the proportion of the total population with specialist degrees or above.

(6) Level of digitization (info). China has entered the digital era, and digitalization is crucial in building smart cities and digital villages, and realizing urban-rural connectivity. Digitalization technology can also effectively detect changes in the ecological environment and respond to and manage negative ecological situations. It is indicated by the number of Internet port accesses used.

5.5.2 Identification and testing of spatial econometric models

The results of the Moran index indicated that there is a significant spatial correlation between R-U-E coupling and coordination, and it is crucial to adopt a spatial panel model to reveal the strength of the impact of spatial effects. In this paper, LM-spatial lag, Robust-spatial lag, LM-spatial error. Robust LM-spatial error test was conducted to determine the spatial measurement model and the results showed that the statistics passed the test of significance at the 1% or 5% level, which indicates that both the spatial lag model and the spatial error model are applicable. Through the Wald test and LR test, it was found that the spatial Durbin model does not degenerate into the spatial lag model and spatial error model, and the choice of the spatial Durbin model for the analysis of spatial effects is the most appropriate. Based on the results of the Hausman test, a fixed-effects model was used to analyze the spatial effects of coupled coordination (Table 7).

TABLE 7 Estimates of spatial measurement model identification.

Test method	Statistical value
LM-lag	7.400***
Robust LM-lag	7.091**
LM-error	29.834***
Robust LM-error	23.144***
Wald-lag	15.350***
Wald-error	14.960***
LR-lag	47.070**
LR-error	58.320***
Hausman	16.65***

5.5.3 Preliminary results of space measurements

The two-way fixed effects model can account for the omitted variables in the time evolution of coupled coordination differences across provinces. Combining R-squared and Log-likelihood statistics, this paper takes the two-way fixed spatial Durbin model as its benchmark model (Table 8).

The coefficient of economic growth level is 0.016 and significant at a 1% statistical level, indicating that there is a positive impact of local economic development on the coupled and coordinated development of R-U-E. The coefficient of the spatial interaction term of economic growth level is 0.055 and significant at a 10% statistical level, indicating that an increase of economic growth level has a certain impact on the coupled and coordinated development of neighboring provinces. The coefficient of external openness is 0.093 and significant at the 1% statistical level, indicating that the external openness of a region has a positive effect on the level of R-U-E coupling and coordination. The coefficient of the spatial interaction term of external openness is −0.521 and significant at the 1% statistical level, indicating that an increase in external openness will inhibit the development of the level of coupling and coordination in neighboring provinces. Government behavior, the level of human capital, and the level of digitalization all have a

TABLE 8 Both fixed effects panel SDM estimation results.

Variables	Time		Ind		Both	
	Coefficients	W×coefficients	Coefficients	W×coefficients	Coefficients	W×coefficients
gdp	0.115***	0.032*	0.026**	−0.081*	0.016**	0.055*
	(0.010)	(0.057)	(0.011)	(0.042)	(0.011)	(0.051)
tec	−0.032	−0.069	0.011	0.061*	0.067	0.053
	(0.004)	(0.038)	(0.006)	(0.014)	(0.006)	(0.042)
open	0.089***	0.156	−0.081***	0.082**	0.093***	−0.521**
	(0.013)	(0.107)	(0.022)	(0.085)	(0.021)	(0.143)
gov	0.117***	1.540***	0.307***	0.087	0.227***	1.439***
	(0.025)	(0.167)	(0.058)	(0.161)	(0.054)	(0.195)
capi	0.946***	1.491**	1.895**	1.986**	1.733***	1.765***
	(0.384)	(0.412)	(0.390)	(0.486)	(0.364)	(0.442)
info	0.064***	0.017**	0.046***	0.011***	0.033***	0.440***
	(0.006)	(0.052)	(0.012)	(0.024)	(0.018)	(0.069)
rho	0.230***		0.546***		0.559***	
	(0.199)		(0.095)		(0.200)	
log L	641.272		812.028		853.757	
R^2	0.638		0.388		0.526	
N	372		372		372	

Note: Standard Error are in parentheses. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

significant positive effect on the coupled and coordinated development of R-U-E in both local and neighboring provinces.

5.5.4 Spatial effects results

In order to reduce the errors that may arise from analyzing explanatory variables by simply using elasticity coefficients, this paper refers to Lesage et al. and adopts the partial differentiation method of SDM to break down the total effect into direct and indirect effects, so as to explore the extent of the influence of each explanatory variable on the coordinated development of R-U-E coupling. The total effect reflects the impact of all spatial unit explanatory variables on local R-U-E coupling and coordinated development, the direct effect reflects the impact of each explanatory variable on R-U-E coupling and coordinated development in the region, and the indirect effect reflects the spatial spillover effect of each explanatory variable on R-U-E coupling and coordinated development in neighboring provinces in the region. From the results, it can be seen that there are some differences in the total, direct and indirect effects of the explanatory variables on the coupled and coordinated development of R-U-E in local and neighboring areas (Table 9).

The level of economic growth has a positive effect and positive spatial spillover effect on the coupled and coordinated development of R-U-E, and the regression coefficients were significantly positive, with direct effect and indirect effect regression coefficients of 0.016 and 0.051, respectively, indicating that an increase of 1% in the level of economic growth increases the level of coupled and coordinated development of R-U-E in the region by 0.016%. At the same time, this leads to 0.051% increase in the level of coupled and coordinated development of R-U-E in the neighboring region. The coordinated sustainable development of urban and rural areas and the harmonious coexistence of human beings and nature are the products of regional economic development at a certain stage. The coupled and coordinated development of R-U-E requires a strong material and economic foundation, and the two are mutually reinforcing. A healthy economy promotes the agglomeration of production factors in towns and cities, and the adjustment and optimization of the industrial structure in villages provides a favorable economic environment for the integrated development of urban and rural areas. Economically developed regions have high levels of primitive capital accumulation, which provides strong financial and fiscal policy support for the construction of urban and rural infrastructures, the introduction of human resources, and ecological and environmental governance, among other things.

The innovation drive has a facilitating effect on the coupled coordinated development of R-U-E, but it does not pass the significance test, indicating that although empirical studies have concluded that technological innovation is conducive to the governance of urbanization, rural development and the ecological environment, the driving force of technological innovation in the coupled coordinated development has still not been clearly demonstrated from the practical point of view.

Openness to the outside world has a positive effect and negative spatial spillover effect on the coupled and coordinated development

TABLE 9 Effect decomposition results for the SDM.

Variable	gdp	tec	open	gov	capi	info
Direct effect	0.016** (0.010)	0.005 (0.006)	0.090*** (0.020)	0.236*** (0.054)	1.436*** (0.321)	0.031** (0.012)
Indirect effect	0.051* (0.044)	0.049* (0.041)	−0.461*** (0.134)	1.367*** (0.165)	1.695** (0.464)	0.394*** (0.085)
Total effect	0.067** (0.045)	0.054 (0.043)	−0.370*** (0.136)	1.603*** (0.163)	3.131*** (0.398)	0.425*** (0.085)

Note: Standard Error is in parentheses. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

of R-U-E, direct effect regression coefficients is 0.090, and indirect effect regression coefficients is −0.461, indicating that an increase of 1% in openness to the outside world, and promote a 0.090% increase in RUE coupling and harmonization in the province. However, it has an inhibitory effect on the coupled and coordinated development of RUE in neighboring provinces. The flow of factors such as technology, talent and ideas in opening up to the outside world promotes the improvement of the level of coupled and coordinated development of R-U-E in the region. However, provinces with strong economic foundations, well-developed infrastructures, and obvious advantages in terms of geography and resources are more prone to attracting external investment and outstanding talents, which further widens the gap in coupled and coordinated development between regions.

Government intervention has a positive effect and positive spatial spillover effect on the coupled and coordinated development of R-U-E, and the regression coefficients were significantly positive, with direct effect and indirect effect regression coefficients of 0.236 and 1.367, respectively, indicating that an increase of 1% in the level of economic growth increases the level of coupled and coordinated development of R-U-E in the region by 0.236%. At the same time, this leads to 1.367% increase in the level of coupled and coordinated development of R-U-E in the neighboring region. The coupled and coordinated development of R-U-E systems has been the focus of the Chinese government's attention for a long time, therefore, the policy arrangements and institutional construction are directly related to the choice of paths for the coupling of the three systems, and the government's intervention provides a favorable policy environment for the coupled and coordinated development of R-U-E.

The level of human capital has a positive effect and positive spatial spillover effect on the coupled and coordinated development of R-U-E, and the regression coefficients were significantly positive, with direct effect and indirect effect regression coefficients of 1.436 and 1.695, respectively. The level of human capital represents the quality of the population, which can promote residents' low-carbon behaviors such as green consumption, green travel and ecological and environmental protection awareness, enhance the degree of civilization of the countryside, reduce ecological and environmental damage and the degree of urban civilization, and this direct and indirect conversion effect continues to promote the coupled and coordinated development of R-U-E.

The level of digitization has a positive effect and positive spatial spillover effect on the coupled and coordinated development of R-U-E, and the regression coefficients were significantly positive, with direct effect and indirect effect regression coefficients of 0.031 and 0.394, respectively. Digital development accelerates cross-regional and urban-rural information exchange and cooperation, promotes scientific and technological innovation and industrial upgrading, enhances productivity, facilitates social development and improves people's lives, thus facilitating the coordinated development of R-U-E coupling.

5.5.5 Regional heterogeneity

As there are certain differences among regions in terms of geographic conditions, natural endowments, and development processes, in order to compare the impact effects of different regions, this paper conducts a regional heterogeneity test (Table 10). In terms of direct effect, the level of economic development has a contributing effect on the level of coordination of the coupling of the seven regions, with Central China > Northwest China > South China > Northeast China > East China > North China > Southwest China, which may be due to the fact that in regions with stronger economic strength, the transfer of the rural population to the cities, which has exceeded the rate of natural population growth over the long term, and the crude mode of economic growth have resulted in the widening of the gap between the urban and rural areas and the destruction of the ecological environment, thus making it more difficult to promote the harmony of man and nature. This shows that it is more difficult for regions such as East China and North China to promote harmony between human beings and nature. The innovation drive has a significant impact on East and North China, and a non-significant impact on other regions. These two regions are concentrated in China's top institutions of higher learning and high-quality people, is the most important incubator of innovation, the invention of patents can be transformed and applied in the process of socio-economic development in the vicinity of the other regions should further increase the cultivation of innovative talents, activate the vitality of innovation. The degree of openness to the outside world has a significant positive impact on East China and a significant negative impact on Southwest China, because the higher the degree of openness to the outside world, the greater the flow of factors, and high-quality factors tend to concentrate in developed regions due to the attraction of high welfare and improved basic public services, thus generating a cumulative causal effect, and the gap between urban and rural areas as well as between regions widens further. Government behavior has a

TABLE 10 Spatial heterogeneity result.

Area	Effect	gdp	tec	open	gov	capi	info
North China	Direct effect	0.052** (0.025)	0.011** (0.022)	−0.088 (0.077)	0.476** (0.291)	12.575** (6.804)	0.137* (0.124)
	Indirect effect	0.109*** (0.041)	−0.009 (0.049)	−0.193 (0.162)	0.926** (0.594)	18.025* (15.882)	0.583** (0.290)
	Total effect	0.161*** (0.056)	0.002 (0.067)	−0.281 (0.228)	1.403*** (0.849)	30.599** (22.378)	0.720** (0.403)
East China	Direct effect	0.053** (0.053)	0.015* (0.009)	0.219*** (0.073)	0.075* (0.309)	0.394** (1.570)	0.108*** (0.034)
	Indirect effect	0.002 (0.234)	0.051 (0.035)	−0.791*** (0.248)	1.908* (1.138)	5.287* (6.582)	0.270** (0.124)
	Total effect	0.055** (0.227)	0.066* (0.037)	−0.572*** (0.300)	1.983** (1.254)	5.681*** (6.711)	0.377** (0.147)
Central China	Direct effect	0.560*** (0.099)	0.010 (0.017)	0.030 (0.223)	1.278** (1.201)	3.663** (4.097)	0.174** (0.068)
	Indirect effect	0.469** (0.186)	0.005 (0.039)	1.248*** (0.411)	0.827* (1.183)	2.528* (4.664)	−0.002 (0.093)
	Total effect	1.029*** (0.226)	0.015 (0.043)	1.278** (0.527)	2.105** (2.325)	6.191** (8.235)	0.172* (0.144)
South China	Direct effect	0.419** (0.190)	0.030 (0.019)	0.007 (0.105)	0.872** (0.401)	0.943 (5.48)	0.011* (0.094)
	Indirect effect	0.612* (0.508)	−0.068** (0.032)	0.576** (0.244)	1.445 (1.120)	7.746** (9.095)	0.224* (0.262)
	Total effect	1.032** (0.566)	−0.038** (0.047)	0.583* (0.299)	2.317* (1.233)	6.803** (9.969)	0.235** (0.281)
Northeast	Direct effect	0.138* (0.070)	0.106 (0.020)	−0.197 (0.157)	0.018** (0.171)	5.594** (7.312)	0.052* (0.102)
	Indirect effect	0.221 (0.140)	0.271 (0.156)	−0.625 (0.420)	0.120 (0.579)	7.204* (12.114)	0.025* (0.261)
	Total effect	0.359* (0.185)	0.323 (0.165)	−0.822* (0.492)	0.138** (0.626)	12.798** (17.011)	0.077* (0.305)
Northwest	Direct effect	0.455*** (0.149)	0.043 (0.017)	−0.465*** (0.160)	0.055** (0.205)	1.778** (1.904)	0.113*** (0.040)
	Indirect effect	0.650** (0.284)	0.072 (0.059)	−1.003 (0.796)	0.767* (0.573)	5.495 (9.524)	0.126 (0.125)
	Total effect	1.105*** (0.345)	0.115 (0.059)	−1.468* (0.816)	0.822** (0.673)	7.273** (10.408)	0.239** (0.123)
Southwest	Direct effect	0.077* (0.105)	0.071 (0.015)	−0.118 (0.084)	0.378*** (0.093)	0.261** (1.374)	0.014** (0.045)
	Indirect effect	0.488* (0.245)	−0.087 (0.061)	−0.190 (0.415)	0.438* (0.501)	5.138* (4.389)	0.116** (0.132)
	Total effect	0.565* (0.313)	−0.016 (0.067)	−0.308 (0.400)	0.816** (0.497)	5.399** (4.840)	0.130** (0.147)

significant positive promotional effect on all seven regions, with the degree of influence in the following order: Central China > South China > North China > Southwest China > East China > Northwest China > Northeast China. Since the implementation of the country's three major strategies, the national and local governments have actively taken measures to promote the coupling and coordination of the three systems, and the Central China region has adopted a strategy that is tailored to the local conditions, and has realized the icing on the cake of urban-rural integration and development, aided by the policies. South and North China are among the regions with large urban-rural disparities and a weak foundation for coordinated development, and the level of coordination has been further enhanced with the tilting of relevant policies. East China's economy feeds back more than direct policy intervention. Policies in the Northwest and Northeast remain underutilized. Human capital contributes significantly and positively to all six regions except South China. Human capital is the endogenous driving force behind the development of villages, towns and cities and the management of the living environment, and plays an "empowering" role in various fields. The greatest impact is in Northeast China and North China, where North China has a strong human capital base, and Northeast China, with the implementation of the national policy of revitalizing old industrial zones and the strategy of rural revitalization, has seen a clear phenomenon of the return of human capital, which has contributed to the coordinated development of the region; South China does not reflect the significant role of human capital. The level of digitization has a significant positive impact on all seven regions. It is being used in various industries as a new industry and is making a positive impact. North China, East China, Central China and Northwest China have a comparable degree of influence, indicating that the construction of digital villages and the construction of smart cities in these regions have achieved some success, South China, Northeast and Southwest should actively introduce digital facilities and technologies to empower coupling coordination. In terms of indirect effects, the level of economic development shows positive spatial spillover effects in North, Central, South, Northwest and Southwest China. Innovation drive generates negative spatial spillovers in South China; The level of openness to the outside world shows negative spatial spillovers in East China and positive spatial spillovers in Central and South China; Government behavior shows spatial spillover effects in North, East, Central, Northwest and Southwest China; Human capital level and digitization level show spatial spillovers in North China, East China, Central China, South China, Northeast China, and Southwest China.

6 Conclusion and outlook

6.1 Conclusion

Based on the synergy theory, this paper elucidates the coupled and coordinated evolution mechanism of China's rural revitalization, new urbanization and ecological environment interactions, and constructs a comprehensive evaluation index system for the RUE composite system. The spatio-temporal evolution, regional differences and spatial effects of the coupled coordination of the three systems were analyzed using the entropy method, the composite index method, the coupled coordination model, the dagum Gini coefficient, the kernel density estimation method, the spatial correlation analysis and the spatial Durbin model. The results are as follows.

Firstly, The composite indices for rural revitalization, new urbanization and the ecological environment are all on the rise, with relatively obvious uneven development across regions.

Secondly, The national R-U-E coupling coordination index exhibits a growing trend from barely coordinated to primary coordinated. The coordination characteristics of Northeast and North China remained unchanged during the study period as barely coordinated and primary coordination. Northwest and Southwest China evolved from on the verge of dysfunction to barely coordinated. South and Central China evolved from barely coordinated to primary coordinated; and East China evolved from primary coordinated to intermediate coordinated.

Thirdly, The differences in coupled and coordinated development across the country and within the region are gradually narrowing. The largest intra-regional differences were found in South China, while the smallest intra-regional differences were found in Central China. The differences between the Northeast and Central China regions was on a widening trend, while the gap between all other regions was on a narrowing trend. Interregional differences are the main factor influencing the overall variance.

Fourthly, there appears to be a spatial spillover effect in the level of coupling coordination of the R-U-E system, the index exhibiting a fluctuating downward trend and the spatial correlation gradually weakening. Aggregation effects were observed in areas with high coupling coordination, as well as in areas with low coupling coordination.

Finally, The level of economic growth, government behavior, the level of human capital and the level of digitalization all make significant contributions and have positive spatial spillover effects on the coupled coordination of the R-U-E system and are the key factors affecting levels and differences in coupled coordination.

6.2 Shortcomings and outlook of the study

This paper also has some shortcomings that need to be further explored in depth in future research. Firstly, the data used in this article are provincial level data, in order to be able to obtain more detailed and reliable conclusions, the data can be specific to the city or county in the future. Secondly, The weights assigned to the indicators are assigned objectively, i.e., entropy value method, ignoring the superiority of subjective assignment, which can be carried out at a later stage with a combination of objective and subjective weight assignment methods. Thirdly, In conducting spatial correlation and spatial measurement analyzes, the spatial weighting matrix used is the spatial distance matrix, and the results of the run will have some deviation for different matrix types, which can be added to the economic distance and proximity distance matrices for comparative analyzes. Fourthly, In this paper, six universal explanatory variables were selected to analyze the spatial effects, and only the spatial effects of the coupling coordination at the national level were analyzed; the spatial effects of each region should be further analyzed comprehensively and contrasted, and explanatory variables consistent with the characteristics of the region should be selected for specific analyzes for different regions, so as to put forward countermeasure proposals that are more in line with the reality of the region and have the right characteristics. Fifthly, Analyzes of the spatial and temporal evolution of the sub-elements of the three systems will be added in subsequent studies.

7 Policy implications

Based on the conclusions reached in the above analysis, this study proposes the following recommendations.

Firstly, Establishment of a sound talent protection policy to inject vitality into the coordinated development of rural revitalization, new urbanization and ecological coupling.

Policies are people-centered in the context of coordinated development. Cities should actively promote the citizenship of migrant workers, improve the basic public service system, and solve the livelihood problems of migrant workers in such areas as housing, healthcare, children's education, employment and old-age pensions. Rural villages should establish a talent strategy of "exogenous incentives" and "endogenous cultivation", attracting the return of urban human capital through land system reform, innovation and entrepreneurship policies, and related welfare incentives, and bringing factors of production such as capital, technology, information and ideas to rural villages, thus promoting the rational flow of factors and facilitating rural development and the improvement of the ecological environment. Increase efforts to train professional farmers, transform traditional agricultural business methods with modern planting and breeding techniques and management concepts, and promote the improvement of agricultural productivity and the growth of farmers' incomes. Ecological environment should increase the ecological environmental protection propaganda, enhance the people's awareness of environmental protection, so that the people from economic rationality to ecological rationality change, and actively participate in the protection and management of the ecological environment.

Secondly, differentiated strategies according to local conditions should implemented with the help of the region's own advantages and adhere to the priority of ecological protection. In the process of urban and rural development, it is necessary to regulate the conflict between the economy and ecology, always adhering to the concept of "green mountains are golden mountains," guarding the ecological red line, adhering to the optimization of ecology, promoting green and low-carbon development, and improving the comprehensive utilization rate of energy. East China should take advantage of its strong economic foundation, play its radiation-driven role, improve the rural governance system, improve the rural ecological environment and strengthen, rural spiritual civilization, while setting an example as a leader in R-U-E coupling and coordination.

With natural resources advantages, the Southwest and Northwest regions have developed ecological economies, enhanced their economic strength, carried out scientific and reasonable spatial planning on the basis of ecology, increased urban and rural infrastructure construction, and realized the equalization of basic public services, so as to promote the coordinated development of R-U-E coupling to a higher level. Taking the revitalization of old industrial zones as an opportunity, the Northeast region has increased its efforts to promote agriculture with industry, bring the countryside to the city, expand openness to the outside world, enhance the inflow of factors such as talent, information and technology, implement an optimized talent strategy, retain and attract talent, and provide a solid foundation for the coordinated development of R-U-E coupling.

North China has the highest degree of coupling and coordination, and it continues to set an example for the roles played by major cities, reducing the differences between regions through a trickle-down effect, further increases in the governance of the ecological environment, transmission of the urban civilization to the countryside, and enhancement of the civilization of the countryside. Based on its own resource endowment and development foundation, Central China continues to follow the path of ecological-economic green and sustainable development. South China should further increase its efforts to revitalize the countryside, integrate the three industries in the countryside, improve the policy inclination of rural construction, introduce talent to achieve the revitalization its human resources, and utilizing its own ecological advantages, develop green eco-industries to improve the quality of life of farmers.

Thirdly, regional cooperation should be strengthened to achieve resource sharing and give full play to the spatial spillover effect of rural revitalization, new urbanization and coordinated development of the ecological environment. East China and South China belong to the more economically developed regions, and should strengthen the cooperation and assistance to the industries, projects and talents of the economically underdeveloped regions in Northeast, Southwest and Northwest China, and actively play a leading role in driving the development of these regions. Relying on the construction of city clusters and city belts within each region, strengthen the linkages among regions, form efficient, coordinated and sustainable urban and rural industrial systems, ecological systems, and public service and governance systems, promote the process of urban and rural marketization, and enhance the ability to provide basic public services and the governance of the ecological environment.

Finally, Enhancing digitalization and empowering the coupled coordination of rural revitalization, new urbanization and ecological environment. Increasing the construction and popularization of new digital infrastructures such as the Internet, the Internet of Things and big data. Strengthening the construction of supporting facilities for digital technology, especially the construction of database resources, building an integrated urban and rural agriculture-related big data platform, improving the mechanism for the establishment, flow and sharing of agricultural big data, and realizing the interconnection of urban and rural data and information.

Data availability statement

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

Author contributions

RZ: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Software, Validation, Visualization, Writing–original draft, Writing–review and editing. QB: Conceptualization, Data curation, Project administration, Resources, Supervision, Validation, Writing–review and editing.

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Conflict of interest

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

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The author(s) declare that no Generative AI was used in the creation of this manuscript.

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