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Coupling study on ecological resilience and urban-rural integrated development in China

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Scientific understanding of China's ecological resilience and urban-rural dynamics supports comprehensive environmental and socio-economic advancement. This research utilizes an integrated coupling coordination framework to examine the relationship among ecological resilience and rural-urban dynamics in 31 Chinese provinces from 2011 to 2022. The spatiotemporal dynamics of ecological resilience-urban-rural coupling are examined through kernel density estimation and complementary methods. An LSTM network is used to forecast trends (2023-2030) and identify underlying patterns. Panel VAR is applied to explore the dynamic interactions between ecological resilience and urban-rural dynamics. The findings reveal regional disparities, with urban-rural dynamics consistently outperforming ecological resilience across all regions, while exhibiting lower variability. The coordination between ecological resilience and urban-rural dynamics shows an upward trend with moderate concentration and distinct regional variations. Projections for 2023-2030 indicate fluctuating yet upward trends in provincial-level coordination. Provincial development transitions from near-imbalance and marginal coordination pre-2026 to primary and intermediate coordination phases post-2026. The coordination levels across the four regions are ranked in descending order as follows: the eastern part of China, followed by the western, midland, and northeast areas. Nationwide analysis reveals significant autocorrelation in ecological resilience (5% level) and urban-rural dynamics (1% level), with urban-rural dynamics exerting a stronger influence on ecological resilience (1% level). This study elucidates the ecological resilience-urban-rural nexus, offering empirical foundations for China's sustainable urban-rural development strategies.

KEYWORDS

ecological resilience, urban-rural integrated development, coupling coordination degree, long short term memory network, panel vector autoregression

1 Introduction

Since the 21st century, China has implemented comprehensive policies promoting urban-rural integration, coordination, and harmonized development to address regional disparities (Zhao et al., 2024). The pivotal 2017 CPC National Congress marked a significant turning point by proposing the establishment and improvement of mechanisms, systems, and policies for urban-rural integration, officially elevating it to the status of a national strategy. As efforts to accelerate urban-rural integrated development progress, urbanization has introduced ecological challenges, including traffic congestion, industrial expansion, and unregulated population growth (Zeng et al., 2022). On the other hand, rural areas have contributed to urban industrial development through resource extraction activities such as coal mining, steel production, and mineral exploitation, further exacerbating ecological degradation in these regions (Li, 2020). Ecological resilience denotes an ecosystem's ability to respond to, adjust to, and rebound from external shocks and disturbances. It acts as an essential foundation for the sustainability of ecological progress (Peng et al., 2024). During a critical period of achieving high-quality modernization goals and promoting accelerated transformation in the new era, the traditional ecological factor-driven model is no longer effective in solving the interweaving problem between ecological resilience and urban-rural integrated development (Zhou and Li, 2020). During urban-rural integration, the ecological challenges faced by cities and the capital flow in ecological security management are practical issues for maintaining ecological resilience and advancing development (De Moraes Hoefel et al., 2021). To advance shared prosperity and balanced regional growth, analyzing and clarifying the coordination between ecological resilience and urban-rural integration holds significant guiding importance.

In the process of promoting regional coordination and common prosperity, ecological resilience and urban-rural integrated development are two complex systems that coexist and influence each other, and can also be studied as two independent systems (Banzhaf et al., 2022). At present, research on ecological resilience and urban-rural integrated development has achieved some results (Zhan et al., 2023; Fang, 2022), and scholars persist in investigating the challenge of rural-urban integrated development through an ecological lens (Shi et al., 2024; Sun et al., 2024). In studying ecological resilience, most international research mainly focuses on ecological capacity restoration (Dakos and Kéfi, 2022) and ecological security assessment (Yuan et al., 2022). Additionally, scholars have extensively explored the development of ecological resilience indicator systems (Shi et al., 2022) and comprehensive evaluation of ecological resilience (Gu H. et al., 2024) in different regions and ecosystems. For urban-rural integrated development, most studies analyze the relationship with land use (Niu et al., 2023), the impact of relevant policies (Wu et al., 2022), and the evolving dynamics of urban-rural integration (Zhao et al., 2024), and then examine the factors influencing urban-rural dynamics. Based on extensive research, the relationship between ecological resilience and urban-rural dynamics is gradually becoming clearer (Kocoglu et al., 2022; Sun et al., 2020). Regarding content, current studies primarily focus on analyzing the evolving characteristics of ecological resilience during urbanization (Peng and Cao, 2023), and exploring the interactive relationship between ecological resilience and rural-urban integration (Zhao et al., 2024). With the growing focus of academia on Environmental Kuznets Curve principles, the relationship linking urbanization, economic construction, and ecological environment protection is gradually being examined by an increasing number of scholars (Zhang et al., 2022; Ahmad and Wu, 2022). With the advancement of research, numerous scholars have discovered that the connection linking urbanization progress and ecological construction does not follow a simple straightforward one-to-one correspondence, but instead exhibits a dynamic and evolving complex interplay (Wang et al., 2019). Regarding research methodologies, scholars have utilized diverse approaches to investigate the interplay linking ecology and rural development. Zhang and Li, (2024) employed various methods, including the simulated annealing-projection pursuit model, to examine the status of rural-urban integration within the context of ecological conservation in the Yellow River Basin. Xiao et al. (2017) utilized a Sankey diagram to visualize energy and material flows, integrating it with an ecological network to quantify urban-rural connections. Firstly, rural-urban integration signifies the expansion of metropolitan regions, population concentration, and industrial growth, which may harm the ecological environments of both cities and countryside (Fang, 2022). Secondly, the restoration of ecological resilience will also affect the speed of industrial and urban construction (Shi et al., 2022). Therefore, to fully address the demands of urbanization development and rural revitalization, researching and clarifying the coordination linking ecological resilience and urban-rural integrated development carries substantial theoretical importance.

The connection linking ecological resilience and rural-urban integration is complex and intricate. Throughout the analysis of research on ecological resilience and rural-urban integration, many researchers have highlighted the interaction between the ecological environment and rural-urban integration (Van Leeuwen, 2015). Nevertheless, the majority of studies concentrate on examining the interplay between urban and rural integrated development and ecological security, with relatively limited attention given to ecological resilience. In addition, research on ecology and urban-rural development mainly stays at a single dimensional perspective (Zheng et al., 2019) or analyzes development trends from a relative difference perspective (Zhan et al., 2021), with few studies using a combination of static and dynamic methods to explore development trends. Following the reform and opening-up policies, aiming to accelerate economic growth, China prioritized industrial development and urbanization (Chen et al., 2016), while overlooking the development of agriculture. The progress of rural-urban integration has spurred consistent economic expansion in cities and countryside alike, yet it has also heightened ecological pressures, posing obstacles to the long-term growth of both economic systems and ecosystems (Liang et al., 2022). Therefore, examining the interaction and synergy between ecological resilience and rural-urban integration in China, and thoroughly analyzing their relationship, holds significant practical importance.

Against this backdrop, this study focuses on 31 provinces in China, constructing a multidimensional assessment framework for ecological resilience and rural-urban integration. Using the Integrated Coupling Coordination Model, it evaluates the synergy linking these two frameworks. Moreover, techniques like kernel density analysis are used to examine the spatiotemporal evolution of their synergistic relationship, while LSTM models are utilized to forecast future trends. Lastly, a PVAR model is employed to investigate the evolving interactions between ecological resilience and rural-urban integration in China. Building on existing research, this research seeks to achieve the following four key advancements: (1) developing an assessment framework to examine the regional distribution patterns of ecological resilience and rural-urban integration; (2) examining the spatiotemporal changes in their coupling coordination degree; (3) predicting future trends in

TABLE 1 Assessment framework for ecological resilience.

First level indicator	Secondary indicators	Third level indicators	Direction
Ecological resilience	Restore ability	The situation where everyone has access to water resources	+
		Coverage ratio of green plants in built-up areas	+
		The area of plants in public gardens *per capita*	+
		Local expenditure level on environmental protection	+
	Adaptability	The utilization level of industrial solid elimination materials	+
		Efficiency of Polluted Water Source Treatment	+
		Efficiency of pollution-free treatment of household waste	+
	Resistance	The emission level of industrial smoke and dust	-
		The discharge level of useless water in industry	-
		Emission level of sulfur dioxide	-

their coupling coordination using the LSTM model; and (4) employing PVAR to reveal the underlying dynamics between ecological resilience and urban-rural integrated development across the nation.

2 Materials and methods

2.1 Ecological resilience level measurement

Based on the Ecological Infrastructure and Landscape Security Pattern framework (Yu et al., 2005), mountains, forests, and water systems are important conditions for coping with urban and rural disasters and balancing restoration capabilities. The demand for ecological services by humans is sustainable, but with increasing human pressure and urbanization erosion, ecosystems are also inevitably impacted. Ecological resilience denotes the capacity of an ecosystem to recover from disturbances and stimuli, encompassing resistance to impact, adaptability, and resilience to aftershocks (Cumming and Peterson, 2017). At present, scholars mainly use methods such as Landscape Ecology (Wang et al., 2024), Emerging ecological footprint (Zhao et al., 2024), and constructing indicator systems (Fu et al., 2024) to measure ecological resilience. This research seeks to comprehensively and accurately capture the ecological resilience across various provinces in China. Based on relevant literature (Yuan et al., 2022; Zhang et al., 2022), ecological robustness evaluation indicators were constructed from three dimensions: restoration ability, adaptability, and resistance, as shown in Table 1. At the same time, this study normalized the data, employing the entropy weighting approach to calculate the specific score of ecological resilience.

2.2 Measurement of urban-rural integration level

At the core essence of rural-urban integration lies fostering a bidirectional flow, equitable exchange, fair sharing, and complementary advancement of resources between cities and countryside, driven by both market mechanisms and policy interventions, with the ultimate goal of achieving mutual prosperity and balanced development across these regions (Fang et al., 2024). Currently, the primary approach for assessing rural-urban integration involves constructing an indicator system (Hu et al., 2024). Urban-rural integration embodies the alignment of modern urbanization and countryside renewal strategies (Zhang S. et al., 2024), encompassing a multidimensional fusion of industrial, cultural, and environmental integration across cities and countryside. Economic integration mainly affects the economic development levels of cities and countryside, as well as the earnings and spending behaviors of their populations. Social integration is predominantly manifested in the development of public services such as pension systems, healthcare, and social insurance. Spatial integration focuses on enhancing living conditions, particularly through improvements in transportation infrastructure. Ecological integration is reflected in environmental quality, green spaces, and the development of ecological infrastructure. This study seeks to comprehensively capture the level of rural-urban integration. Referring to relevant literature (Li, 2024), an indicator system was developed from four dimensions: industrial connectivity, cultural cohesion, territorial linkage, and environmental harmonization. Specific indicators are displayed in Table 2. Simultaneously, this study normalized the data, employing the entropy weighting approach to calculate the specific score of rural-urban integration.

2.3 Integrated coupling coordination assessment framework

The Integrated Synergy Assessment Framework primarily examines the interdependent coordination relationship among various subsystems in complex systems, and evaluate the overall coordination level by analyzing the degree of dependence between subsystems (Yang et al., 2020). The pivotal elements of the Coupling Coordination Degree Model are "interaction" and "harmonization level". Coupling refers to the interplay among systems, whereas coordination degree primarily assesses the harmonious interplay between subsystems (Jiang et al., 2022). The core concept of the Coupling Coordination Degree Model revolves around envisioning

TABLE 2 Assessment framework for rural-urban integration.

Primary indicator	Subordinate metrics	Third level indicators	Direction
Rural-urban integration	Economic integration	The situation of economic development	+
		Urban-rural wage gap	-
		Difference in consumption across cities and countryside	-
		Dual contrast ratio	+
	Social integration	Level of pension coverage across cities and countryside	+
		Level of joblessness insurance coverage	+
		Level of *per capita* medical disparity across cities and countryside	-
		The documented rate of unemployment within the city	-
		The extent of educational investment in metropolitan and countryside regions	+
	Space integration	Personal car ownership level	+
		Urbanization rate	+
		Comparison coefficient of *per capita* transportation and communication between urban and rural areas	-
	Ecological integration	Harmless treatment of household waste	+
		Forest coverage	+
		Popularization of public toilets	+

the overall system as multiple interrelated subsystems, whose interactions affect the operational efficiency and sustainable development of the entire framework. The Coupling Coordination Degree Framework is currently utilized in multiple fields such as ecology, sociology, and economics (Gu J. et al., 2024). Referring to Zhang Pei's research (Zhang P. et al., 2024), the article chooses to employ the Integrated Synergy Assessment Framework to evaluate the interplay between ecological resilience and rural-urban integrated development in China. The specific formula is shown in Equations 1–3.

$$\boldsymbol{D} = \sqrt{C \times T} \tag{1}$$

$$\boldsymbol{C} = \mathbf{2}\sqrt{U_1 \times U_2 \big/ (U_1 + U_2)^2} \tag{2}$$

$$\boldsymbol{T} = \alpha U_1 + \beta U_2 \tag{3}$$

In the formula: D is the coupled co scheduling; C indicates the level of interaction, U_1 is the ecological resilience level, and U_2 is the urban-rural integrated development level; T serves as the holistic coordination index of ecological resilience and rural-urban development level; α and β are undetermined coefficients, and this study considers them equally important, both set to 0.5.

2.4 Kernel density estimation

Kernel Smoothing serves as a distribution-free technique primarily employed to approximate the density function of variables and smooth the data to obtain smooth and continuous density estimates (Sheather and Jones, 1991). Kernel Density Estimation can adapt to multiple distribution types and is beneficial for identifying the distribution structure of data. It is mainly used for research in data exploration, visualization, and other areas (Li et al., 2023). Equation 4 is the formula (Wahbah et al., 2022) for Kernel Density Estimation.

$$\boldsymbol{f}(\boldsymbol{x}) = \frac{1}{nh}\sum_{i=1}^{n} k\left(\frac{x_i - \bar{x}}{h}\right) \tag{4}$$

Within the equation: f(x) represents the kernel density estimation; k denotes the kernel function; n is the sample size; h indicates the bandwidth; x_i corresponds to the observed data point; and $\bar{x}$ denotes the average.

2.5 Recurrent neural network with memory cells

The LSTM model is a specialized neural network architecture extensively applied in areas like natural language understanding and graphics processing. LSTM is improved based on recurrent neural networks, processing sequence information through special gating units and outputting relevant results. This model controls the selective retention and forgetting mechanism of historical information, and uses gate units to construct internal information flow paths to achieve information transmission and updating, thereby achieving effective processing of long sequence data (Yadav and Thakkar, 2024). LSTM is capable of handling long-range dependencies, adept at handling time-series data, and has strong memory and learning abilities, able to capture complex patterns and patterns. This study employs the LSTM model to forecast the harmonization level of ecological resilience and rural-

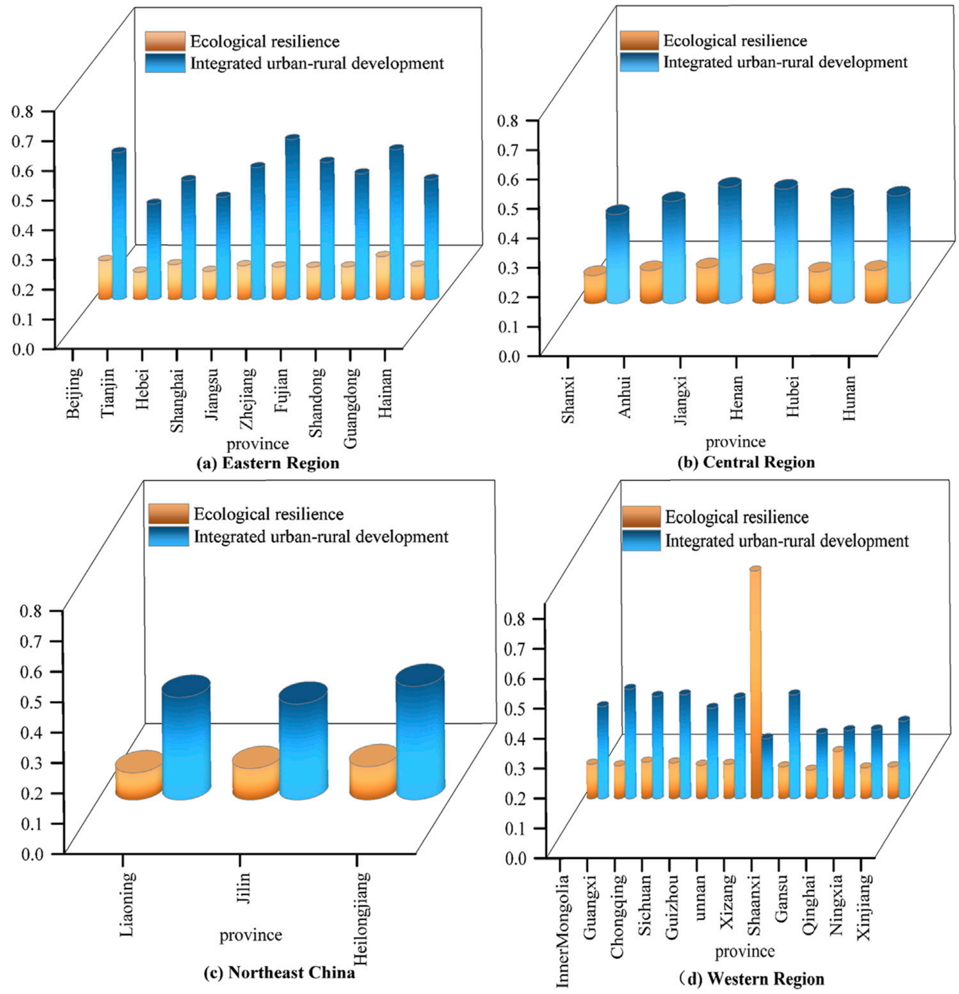

FIGURE 1
Comparison of provincial ecological resilience level and urban-rural integrated development level. **(a)** Eastern region, **(b)** Central region, **(c)** Northeast China, **(d)** Western region.

urban development in 31 provinces of China from 2011 to 2022, and examines its characteristics.

2.6 Panel VAR (PVAR)

To further analyze the interactive dynamics between ecological resilience and urban-rural integrated development, this study selected Panel Vector Autoregression proposed by Sims (Yang et al., 2024) as the tool and used Stata software for data validation. The PVAR model can utilize panel data to process the relationships between multiple variables, reveal their dynamic effects, increase sample size, and better reflect the dynamic characteristics of the data. In addition, the dynamic effects between variables can be studied through impulse response functions, capturing the immediate and enduring impacts of one variable on others. Equation 5 is the specific model of Panel Vector Autoregression (Sigmund and Ferstl, 2021).

$$\boldsymbol{Y}_{i,t} = \alpha_0 + \sum_{j=1}^{k} \alpha_j Y_{i,t-j} + b_i + c_t + d_{i,t} \tag{5}$$

Among them, i is an individual, representing different provinces; t represents time, indicating different years; $Y_{i,t}$ represents the m-dimensional vector of observable random variables for region i during period t; α_0 is the intercept term vector; α_j denotes the m-dimensional coefficient matrix of the delayed variable; $Y_{i,t-j}$ are the j order lagged terms of endogenous variables; b_i represents a region-specific fixed effect; c_t denotes the temporal effect; $d_{i,t}$ are random error terms.

2.7 Data sources

This research employs longitudinal data across 31 regions in mainland China, excluding Taiwan, Hong Kong, and Macau, covering the years 2011–2022. The dataset was primarily obtained from authoritative publications, including the China

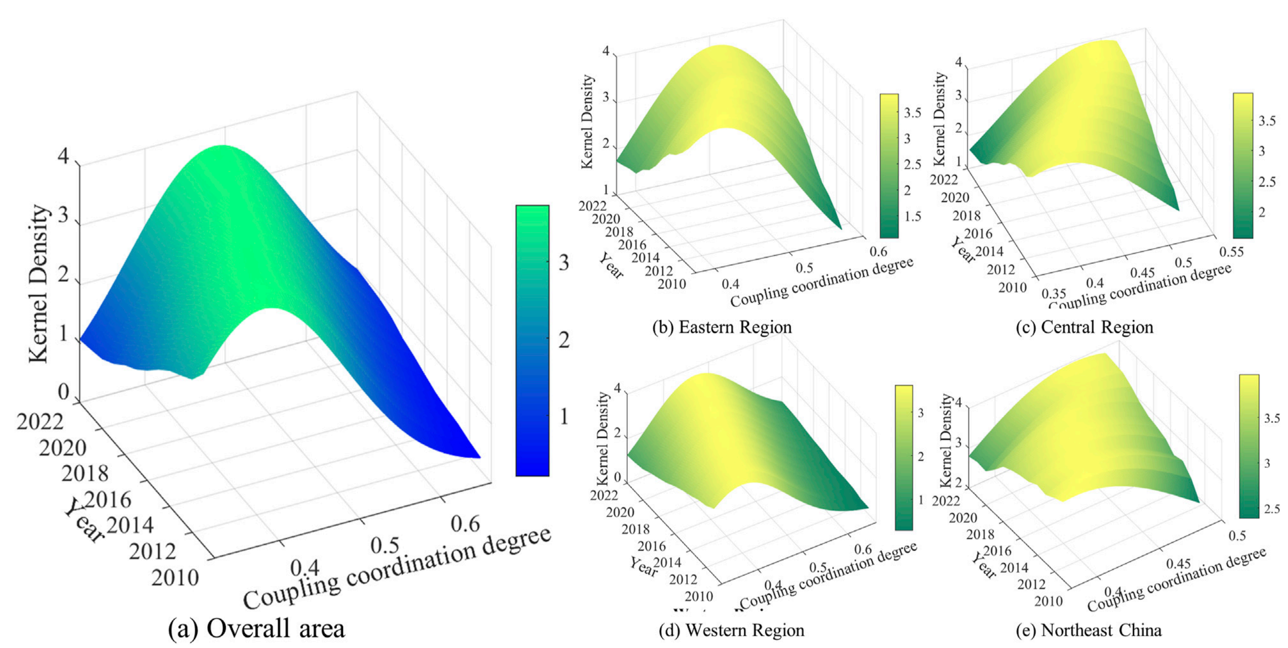

FIGURE 2
The kernel density of the harmonization level between ecological resilience and rural-urban integration. **(a)** Overall area, **(b)** Eastern region, **(c)** Central region, **(d)** Western region, **(e)** Northeast China.

Statistical Yearbook, China Energy Statistical Yearbook, China Environmental Statistical Yearbook, China Science and Technology Statistical Yearbook, and China Industrial Statistical Yearbook. Incomplete data entries were resolved through interpolation techniques to ensure dataset integrity.

3 Results

3.1 Comparative analysis of ecological resilience level and urban-rural integrated development level in different regions

As shown in Figure 1, an examination of ecological resilience and urban-rural integrated development levels across regions indicates that urban-rural integrated development generally exceeds ecological resilience, with ecological resilience displaying greater variability. Specifically, Xizang demonstrates the highest ecological resilience level at 0.7612, while Liaoning records the lowest at 0.0896. Regionally, ecological resilience is ranked from highest to lowest as follows: western, eastern, central, and northeastern areas. Conversely, Zhejiang leads in urban-rural integrated development with a score of 0.5395, whereas Xizang trails at 0.2010. The regional ranking for urban-rural integrated development, from highest to lowest, is eastern, central, northeastern, and western regions. Notably, Xizang is the only province where ecological resilience exceeds urban-rural integrated development; all other provinces exhibit the opposite trend.

A detailed analysis of the eastern region reveals that Guangdong boasts the highest level of ecological resilience, while Tianjin records the lowest. In terms of urban-rural integrated development, Zhejiang leads, whereas Tianjin trails behind. In the central region, Jiangxi exhibits the highest ecological resilience, with Shanxi at the lowest level. Similarly, Jiangxi also leads in urban-rural integrated development, while Shanxi ranks last. Within the northeastern region, Heilongjiang demonstrates the highest ecological resilience, contrasting with Liaoning, which has the lowest. Heilongjiang also tops the urban-rural integrated development ranking, with Jilin at the bottom. In the western region, Xizang has the highest ecological resilience, while Gansu has the lowest. For urban-rural integrated development, Guangxi leads, and Xizang ranks last.

3.2 The temporal variation patterns of the harmonization level between ecological resilience and rural-urban synergy

An in-depth examination of the temporal dynamics of the harmonization level between ecological resilience and rural-urban synergy in China (Figure 2) indicates that the harmonization level across regions generally displays an upward trend, with data showing a tendency toward concentration, though not markedly so. Firstly, examining the characteristics of overall regional kernel density changes, the density curve progressively moves rightward, reflecting an enhancement in the coordination between ecological resilience and urban-rural integrated development across provinces. The primary peak height of the density curve fluctuates with an upward trend, while the distribution pattern remains relatively consistent, indicating a gradual narrowing of disparities in harmonization levels among provinces. The data demonstrates a trend toward centralization, though the effect is not

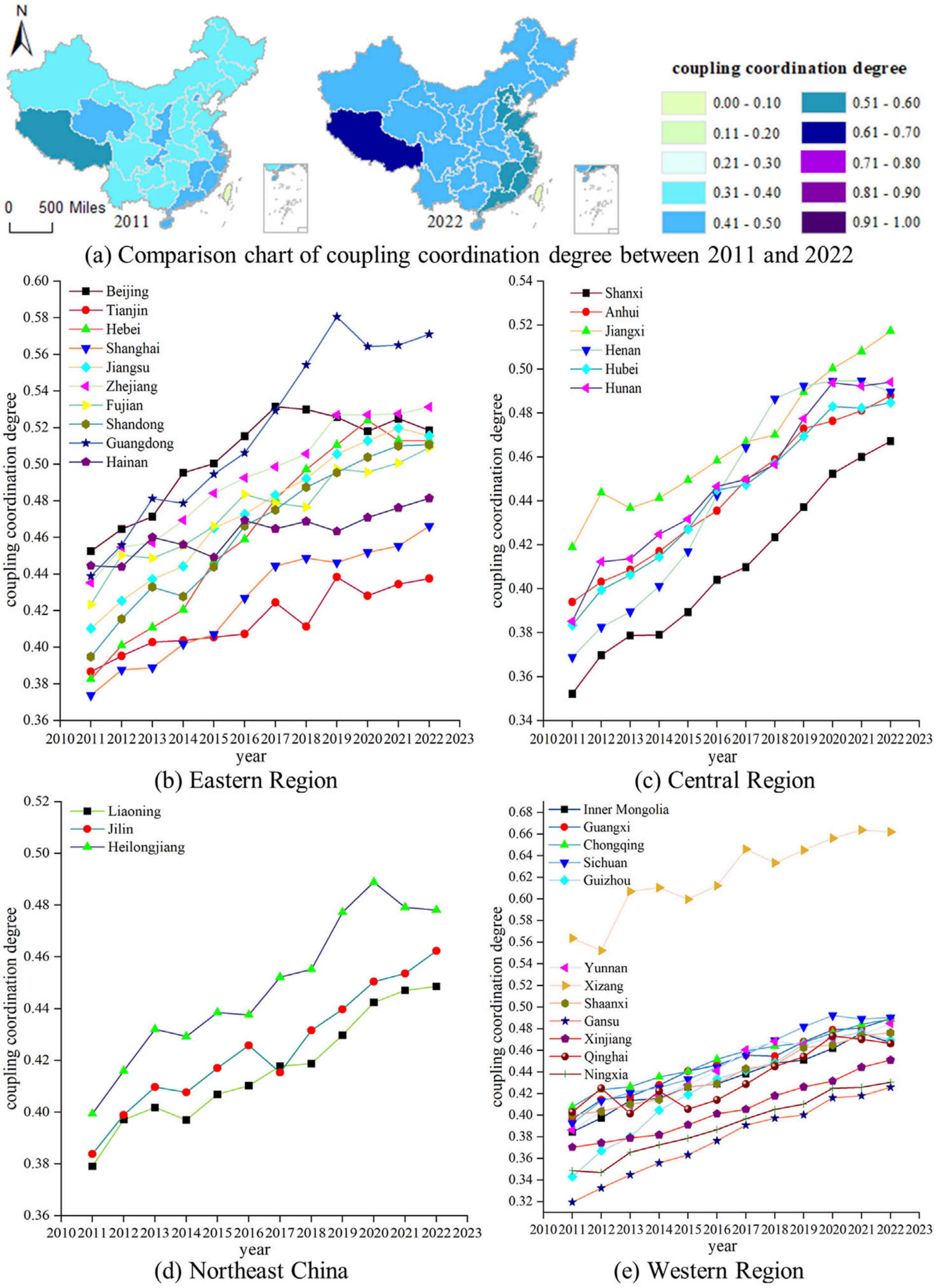

FIGURE 3
Spatial variation patterns of harmonization level between ecological resilience and rural-urban integration from 2011 to 2022. **(a)** Coupling coordination degree between 2011 and 2022, **(b)** Eastern region, **(c)** Central region, **(d)** Northeast China, **(e)** Western region.

pronounced. The kernel density curve consistently maintains a unimodal shape, and throughout the study period, no multipolarity in coupling coordination among provinces was observed.

Examining the characteristics of kernel density changes in the eastern region, the density curve progressively moves rightward, with the primary peak height displaying a varying upward trend. The distribution pattern narrows over time, and the density curve consistently retains a unimodal state. Throughout the study period, no multipolarity in coupling coordination among provinces was observed. In the central region, the density curve also shifts rightward, with no significant change in the primary peak height. The curve's distribution gradually narrows, maintaining a unimodal shape. For the western region, the density curve moves rightward, with the primary peak height fluctuating in an upward trend. The curve's shape gradually narrows, consistently retaining a unimodal state. In Northeast China, the density curve also shifts rightward, with the primary peak height fluctuating and rising. The curve's distribution pattern gradually narrows, maintaining a unimodal state throughout the study period.

3.3 The geographical distribution patterns of the harmonization level between ecological resilience and rural-urban integration

Examining the spatial variation patterns of the harmonization level between ecological resilience and urban-rural integration, as depicted in Figure 3, the harmonization level in each province shows an increasing trend, though the extent of change varies. Guangdong experienced the most significant change, with its coordination degree rising from 0.4389 in 2011 to 0.5710 in 2022, an increase of approximately 0.1321. In contrast, Hainan showed the smallest change, increasing from 0.4445 in 2011 to 0.4814 in 2022, a rise of about 0.0369. Overall, Xizang has the highest coupling coordination level, primarily in the barely coordinated and primary coordinated stages, while Gansu has the lowest, mainly in the mild imbalance and near imbalance stages. In 2011, most regions were in the mild imbalance stage, with 20 provinces falling into this category. Ten provinces, including Shaanxi, Qinghai, Chongqing, Jiangsu, Jiangxi, Fujian, Zhejiang, Guangdong, Hainan, and Beijing, were on the verge of imbalance, while Xizang was in the minimally balanced stage. By 2015, the count of provinces in the mild imbalance phase decreased to four, while 25 provinces were on the verge of imbalance, with Beijing and Xizang remaining in the minimally balanced phase. In 2018, Gansu was in mild imbalance, Zhejiang, Guangdong, and Beijing were in barely coordinated, Xizang reached primary coordinated, and the remaining 26 provinces were near imbalance. From 2021 to 2022, 22 provinces were near imbalance, eight were barely coordinated, and Xizang remained in the primary coordinated stage.

3.4 LSTM model forecasts the harmonization level between ecological resilience and urban-rural integration from 2023 to 2030

Using the LSTM model to forecast the harmonization level between ecological resilience and rural-urban integration in 31 provinces from 2023 to 2030, the harmonization level in each province exhibits a fluctuating and rising pattern. The LSTM model can effectively combine historical data of ecological resilience and urban-rural integrated development coupling coordination, reveal the inherent changes in data, and predict the future trends of data. The model training of this study was conducted on servers configured with i9-14900KF 3.2GHz CPU, 128G RAM, and NVIDIA GeForce RTX 3090 24GB GPU. The entire experimental process was implemented using the MATLAB computational platform and the TensorFlow machine learning library. The Python release is 3.8.16, PyTorch version is 1.13.1, and CUDA version is 11.7. During the training process, the model parameters were iteratively optimized with the SGD algorithm, a step size set to 0.002, and the MSE loss function, completing a total of 1,000 iterations. In addition, this study divided the dataset into training and testing sets by year, using data from 2011 to 2019 as the training set and data from 2020 to 2022 as the testing set. To assess the robustness of the LSTM framework, the harmonization degree of ecological resilience and rural-urban integration in each province from 2020 to 2022 was initially predicted and compared with real data, as shown in Figure 4. Through data comparison, there is no significant error between the predicted data and the actual data from 2020 to 2022. The R^2 of the model is about 0.9379, indicating good model stability. Based on the predicted data in Figure 4, the harmonization level between ecological resilience and rural-urban integration in each province will fluctuate and rise from 2023 to 2030. According to the predicted data of the harmonization level between ecological resilience and urban-rural integration from 2023 to 2030, it can be understood that before 2026, each province is mainly in the stage of near imbalance and minimal coordination, and after 2026, each province is primarily in the stage of basic coordination and intermediate coordination. Overall, the ranking of the harmonization level between ecological resilience and rural-urban integration in the four major regions, from highest to lowest, is the coastal region, western region, central region, and northern region.

Firstly, the predicted data for the harmonization level between ecological resilience and rural-urban integration in the eastern regions were analyzed. Guangdong demonstrates the most notable progress, moving from the minimally balanced stage in 2023 to the well-balanced stage by 2030. In contrast, Tianjin has the lowest level of harmonization in the coastal area, progressing from the near imbalance stage in 2023 to the basic balanced stage by 2030. In the central region, the predicted data for coupling coordination are divided into four tiers. The first tier includes Henan and Jiangxi, which progress from the minimally balanced stage to the intermediate balanced stage. The second tier comprises Hubei, moving from near imbalance to intermediate coordination. The third tier consists of Anhui and Hunan, advancing from barely coordinated to primary coordinated. The fourth tier is Shanxi, progressing from near imbalance to primary coordinated. In the Northeast region, Jilin and Heilongjiang advance from near imbalance to intermediate coordination, while Liaoning moves from near imbalance to primary coordination. In the western region, the predicted data are also divided into four tiers. The first tier includes Xizang, transitioning from primary coordinated to good coordinated. The second tier comprises Guangxi, Chongqing, and Sichuan, advancing from barely coordinated to intermediate coordinated. The third tier includes Qinghai, Xinjiang, Inner Mongolia, Shaanxi, Guizhou, and Yunnan, progressing from near imbalance to intermediate coordination. The fourth tier consists of Gansu and Ningxia, moving from near imbalance to primary coordinated.

3.5 The dynamic interaction effect between ecological resilience and urban-rural integrated development

This study utilizes the PVAR framework to analyze the interactive dynamics between ecological resilience and rural-urban integration using longitudinal data from 31 provinces spanning 2011 to 2022.

3.5.1 Stability test and determination of optimal lag order

To address potential heteroscedasticity, this study first applies logarithmic transformation to the data and then conducts stationarity tests to avoid issues of “spurious regression.” The

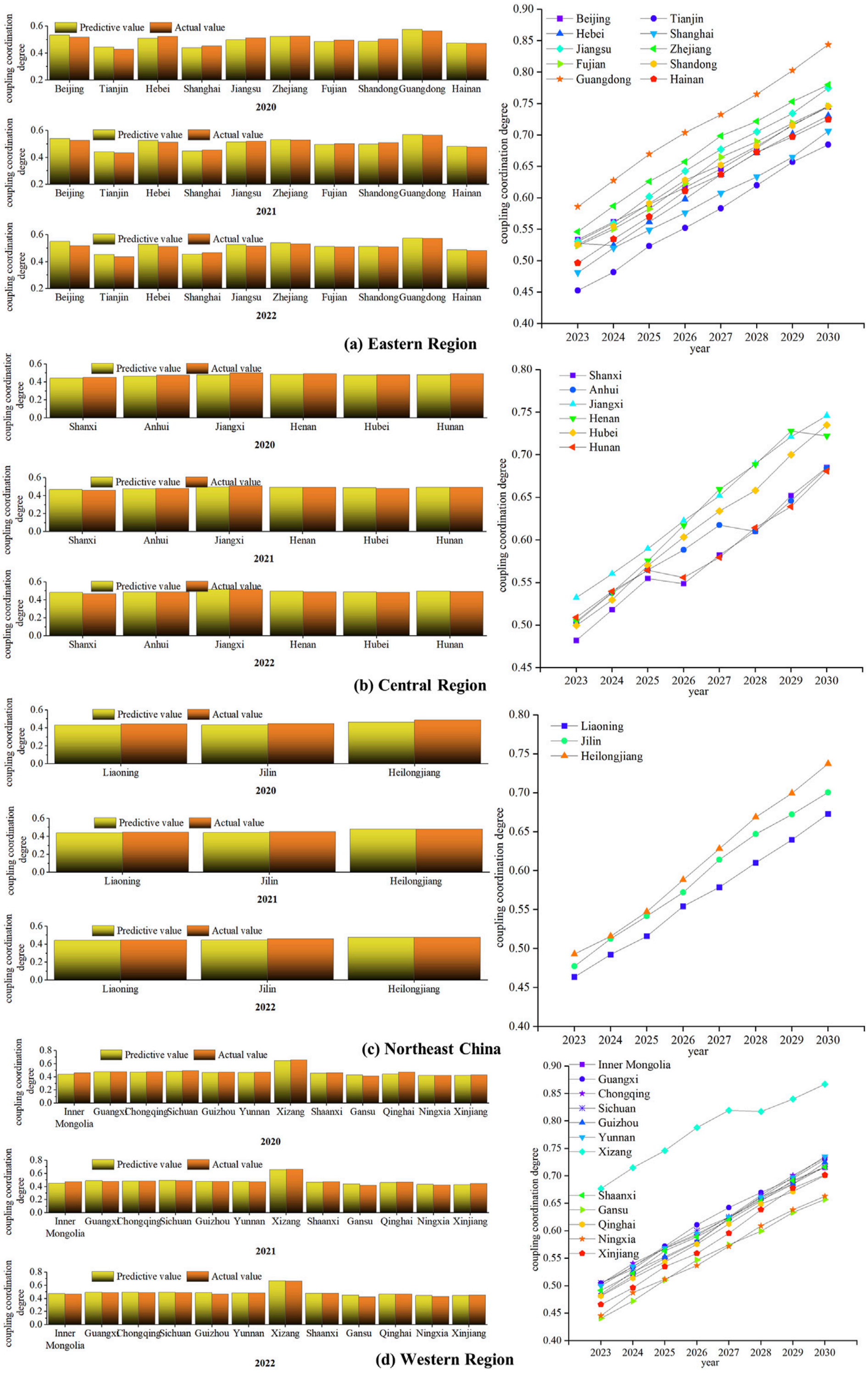

FIGURE 4
Neural network prediction data on the harmonization level between ecological restoration capacity and rural-urban development from 2020 to 2030. **(a)** Eastern region, **(b)** Central region, **(c)** Northeast China, **(d)** Western region.

stationarity of the data is assessed through the IPS, HT, and PP tests, with the outcomes displayed in Table 3. To ensure data stability, all variables except urban-rural integrated development (x2) in the national region undergo first-order differencing. This includes ecological resilience (x1) in the national region, as well as both ecological resilience (x1) and urban-rural integrated development (x2) in other regions. Furthermore, the ideal lag period is identified using the lowest values of the AIC, BIC, and HQIC criteria. As indicated in Table 4, the ideal lag period for the overall, coastal, inland, and northern regions is determined to be

TABLE 3 Evaluation index system for ecological resilience.

	Variable	IPS	HT	PP
National Region	dln_x1	−8.584***	−10.509***	433.519***
	ln_x2	−2.741***	−2.7840***	88.497**
Eastern Region	dln_x1	−4.864***	−6.372***	147.046***
	dln_x2	−4.752***	−3.522***	122.347***
Central region	dln_x1	−3.853***	−2.654***	89.443***
	dln_x2	−3.479***	−2.482***	66.183***
Western Region	dln_x1	−5.152***	−6.913***	175.967***
	dln_x2	−4.908***	−7.699***	161.835***
Northeast China	dln_x1	−3.228***	−5.119***	64.754***
	dln_x2	−2.609***	−3.005***	30.673***

dln_x1 is the first-order differential variable of variable ln_x1, and dln_x2 is the first-order differential variable of variable ln_x2. Same below.

TABLE 4 Determination of the ideal lag period.

Order of lag		1	2	3
National Region	AIC	−3.961	−3.868	−3.466
	BIC	−42.670	−29.674	−16.369
	MQIC	−19.647	−14.326	−8.694
Eastern Region	AIC	−6.993	−8.889	−3.741
	BIC	−32.125	−25.644	−12.119
	MQIC	−16.824	−15.442	−7.018
Central region	AIC	−14.847	−8.096	−3.079
	BIC	−33.850	−20.764	−9.413
	MQIC	−21.480	−12.517	−5.289
Western Region	AIC	−7.259	−2.774	−0.432
	BIC	−34.579	−20.987	−9.538
	MQIC	−18.135	−10.024	−4.057
Northeast China	AIC	−11.745	−6.754	−4.673
	BIC	−22.429	−13.877	−8.235
	MQIC	−13.218	−7.736	−5.164

1. Consequently, subsequent analyses will construct models using a first-order lag.

3.5.2 GMM parameter estimation

The GMM parameter estimation was performed using the ideal lag period, with results displayed in Table 5. In the national region, ecological resilience significantly affects itself at the 5% level but shows no significant influence on rural-urban integration. Conversely, rural-urban integration significantly impacts ecological resilience at the 1% level and itself at the same level. This indicates that regional ecological resilience hinders its own growth, rural-urban integration restrains ecological resilience, and rural-urban integration fosters its own progress. In the eastern region, ecological resilience exhibits no significant impacts on its own state or rural-urban integration. However, rural-urban integration significantly influences ecological resilience but not its own state. Within the central region, ecological resilience significantly influences itself but not urban-rural integration, while urban-rural integration shows no significant effects. In the western region, neither ecological resilience nor urban-rural integration demonstrates significant differences. In the Northeast region, ecological resilience significantly influences itself but not urban-rural integration. Urban-rural integration significantly impacts ecological resilience but not itself.

3.5.3 Impulse response analysis

Perform impulse response analysis on ecological resilience and urban-rural integrated development (Figure 5). From a national regional perspective, when faced with standard deviation shocks from ecological resilience, urban-rural integrated development exhibits a strong negative response, with the greatest response occurring around stage 1. When facing the standard deviation shock of urban-rural integrated development, ecological resilience shows a negative response, with the maximum response occurring around stage 1. When facing the standard deviation shock of ecological resilience, ecological resilience first shows a positive response, then gradually decreases to negative, and then gradually rises to stabilize around 0. When facing the standard deviation impact of rural-urban integration, the response of rural-urban integration is positive and gradually decreases.

From the perspective of the eastern and central regions, urban-rural integration exhibits a strong negative response to standard deviation shocks from ecological resilience, while ecological resilience shows a positive response to shocks from urban-rural integration. When facing shocks from ecological resilience, ecological resilience initially responds positively, then gradually declines and stabilizes near zero. Similarly, when exposed to shocks from rural-urban integration, the response is initially positive but gradually declines and stabilizes around zero. In the western region, urban-rural integration responds positively to shocks from ecological resilience, and ecological resilience shows a positive response to shocks from urban-rural integration. When

TABLE 5 Estimation of GMM parameters of PVAR model.

Region	Variable	Ecological resilience	Urban-rural integrated development
National Region	Ecological resilience	−0.156**	−0.044
	Urban-rural integrated development	−0.168***	0.969***
Eastern Region	Ecological resilience	0.052	−0.011
	Urban-rural integrated development	1.833**	−0.154
Central region	Ecological resilience	0.436**	−0.086
	Urban-rural integrated development	0.304	−0.060
Western Region	Ecological resilience	−0.116	0.080
	Urban-rural integrated development	0.234	−0.134
Northeast China	Ecological resilience	−0.304*	−0.035
	Urban-rural integrated development	1.782***	0.086

ecological resilience faces its own shocks, it initially responds positively, then gradually declines and stabilizes near zero. Likewise, urban-rural integration responds positively to its own shocks, gradually decreasing and stabilizing around zero. In the Northeast region, urban-rural integration initially shows a negative response to shocks from ecological resilience, gradually decreasing over time. Conversely, ecological resilience responds positively to shocks from urban-rural integration, increasing from zero. When ecological resilience faces its own shocks, it initially responds positively, then gradually declines and stabilizes near zero. Similarly, urban-rural integration responds positively to its own shocks, gradually decreasing and stabilizing around zero.

3.5.4 Variance decomposition

To assess the interaction between ecological resilience and rural-urban integration, as shown in Figure 6. According to the variance decomposition results, ecological resilience has the greatest explanatory power for itself, and the impact of rural-urban integration gradually becomes apparent after the second period. "The internal variance of the national region continues to change, and the internal variance of the four major regions tends to stabilize after the third period." Ecological resilience contributes 95.6% nationwide, while urban-rural integrated development only accounts for 4.4%. Ecological resilience in the eastern region accounts for 84.1%, while urban-rural integrated development only accounts for 15.9%. Ecological resilience in the central region accounts for 98.8%, while urban-rural integrated development only accounts for 1.2%. Ecological resilience in the western region accounts for 96.4%, while urban-rural integrated development only accounts for 3.6%. The ecological resilience in Northeast China accounts for 71.8%, while urban-rural integrated development only accounts for 28.2%. Urban-rural integrated development is influenced by its own and ecological resilience, and tends to stabilize nationwide by the sixth period, central regions by the fourth period, and eastern, western, and northeastern regions by the second period. Nationwide, urban-rural integrated development accounts for approximately 98.4% of its own contribution, while ecological resilience accounts for approximately 1.6%. Rural-urban integration in the eastern region accounts for approximately 96.3%, while ecological resilience accounts for approximately 3.7%. Rural-urban integration in the central region accounts for about 92.5% of the total, while ecological resilience accounts for about 7.5%. Urban-rural integrated development in the western region accounts for about 95.8% of the total, while ecological resilience accounts for about 4.2%. Urban-rural integrated development in Northeast China accounts for approximately 98.8%, while ecological resilience accounts for approximately 1.3%. Overall, ecological resilience and urban-rural integrated development have a long-term mutual influence.

4 Discussion

Ecological resilience and urban-rural integration represent two major themes in ecological and economic geography, respectively, both exhibiting distinct spatial correlation characteristics. Research findings indicate significant regional heterogeneity in the levels of ecological resilience and urban-rural integration across different areas of China. This research finding aligns with earlier studies on the relationship between urban construction and ecological development (Wang et al., 2021; Wu et al., 2021). The research on Ethiopia also emphasizes that the development of urbanization affects the level of land use, and there is a clear relationship between urbanization and ecological change (Ayenachew and Abebe, 2024). Specifically, Xizang exhibits the highest level of ecological resilience. Characterized by mountainous terrain and a high proportion of ecological space, the region has established a robust ecological security barrier. (Wu et al., 2023). The region with the lowest level of ecological resilience is Liaoning, mainly due to the rapid decline in arable land and forest area with the expansion of construction land (Yao et al., 2024). Zhejiang exhibits the most advanced rural-urban integration, while Xizang ranks the lowest. Zhejiang has consistently refined its policies and regulations, leading China through the three stages of urban-rural relations: breaking barriers, achieving coordination, and advancing integration. (Ke, 2024). Due to the insufficient high-quality talents in rural areas and the lack of distinctive industrial development, the advancement of urban-rural integrated development in Xizang remains significantly underdeveloped. In the process of urbanization development, people are paying more and more attention to correctly safeguarding the

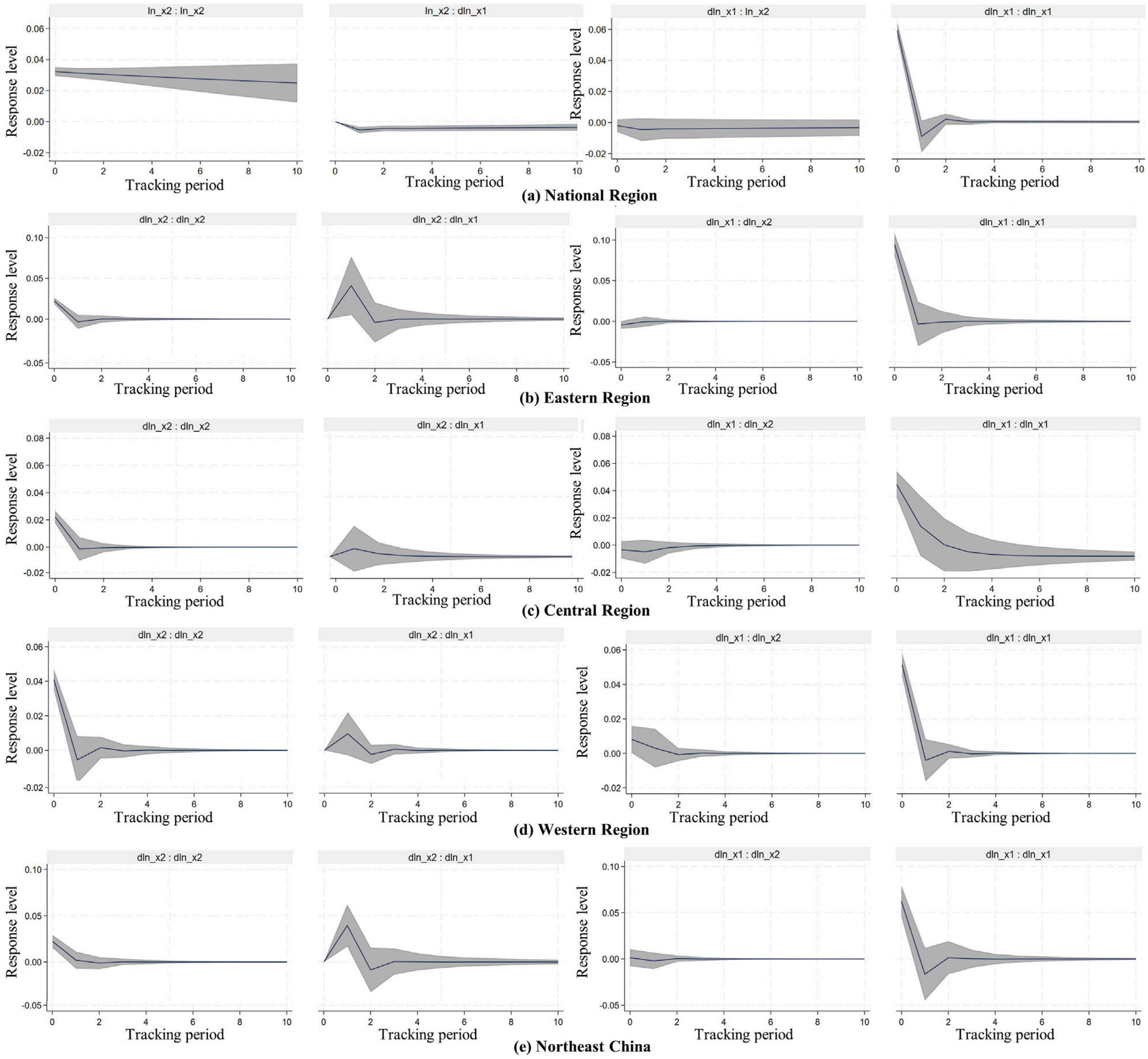

FIGURE 5
Impulse response of ecological resilience and rural-urban integration. **(a)** National region, **(b)** Eastern region, **(c)** Central region, **(d)** Western region, **(e)** Northeast China.

friendly relationship between society and ecology (Vidal et al., 2024). Meanwhile, previous research has shown an overall upward trend in the synergy between urbanization and ecological security in China (Wang, 2022; Xin et al., 2021), which is also confirmed by this article. The overall coupling coordination degree between ecological resilience and rural-urban development across China exhibits a rising trend, with data indicating a tendency toward concentration, though not prominently. From the perspective of natural factors, urban-rural integration promotes regional environmental protection and enhances ecological resilience. (Pickett et al., 2016). Research on urban development in the United States also emphasizes that urban construction is increasingly focused on ecological protection and sustainable development (Jepson Jr and Edwards, 2010). The research findings reveal that Guangdong exhibits the most significant increase in the synergy between ecological resilience and rural-urban development. Through initiatives such as mountain closure, ecological migration, and improvements to the forestry carbon trading mechanism, Guangdong has explored the cultural value of its ecosystems and continuously strengthened regional ecological resilience. From a socio-economic perspective, urban-rural integration has mobilized local labor, fostered coordinated economic development, supported the green transformation of rural infrastructure, and enhanced ecological resilience across urban and rural landscapes (Sigwela et al., 2017). The research results indicate that Xizang has the highest coupling of ecological resilience and urban integration. As urban-rural integration progresses and economic cycles between urban and rural areas are realized, the expansion of ecological agriculture and eco-tourism has spurred local investment in ecological protection and

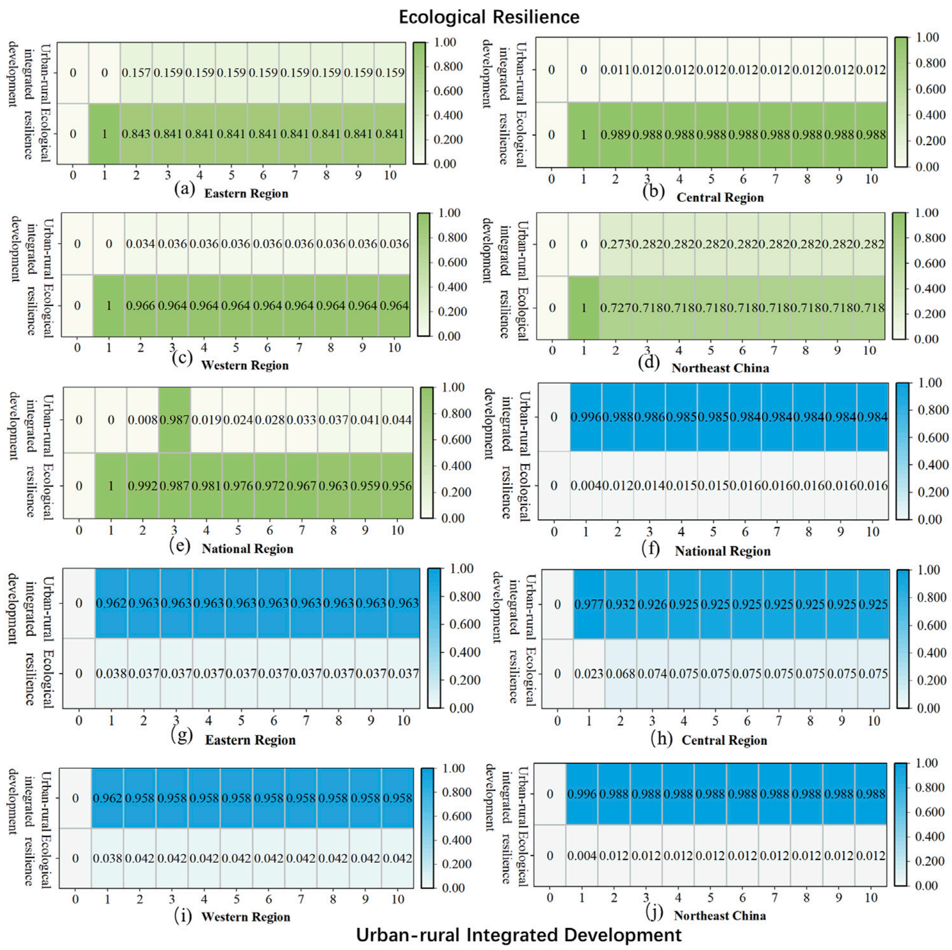

FIGURE 6
Variance decomposition results of each variable. **(a)** Ecological resilience in the eastern region, **(b)** Ecological resilience in the central region, **(c)** Ecological resilience in the western region, **(d)** Ecological resilience in northeast China, **(e)** Ecological resilience in the national region, **(f)** Rural-urban integration in the national region, **(g)** Rural-urban integration in the eastern region, **(h)** Rural-urban integration in the central region, **(i)** Rural-urban integration in the western region, **(j)** Rural-urban integration in northeast China.

strengthened regional ecological resilience. From a policy perspective, urban-rural integration incorporates ecological protection into planning through measures such as ecological red lines and compensation mechanisms, encouraging regions to prioritize the ecological environment and strengthen ecological resilience (Alola et al., 2019).

However, this study mainly utilizes the synergy model to analyze the trends and patterns of the coordination level between ecological resilience and urban-rural integration from a human factors perspective. Natural factors, which also play a significant role, should be more thoroughly investigated in subsequent studies. Investigating the interplay between ecological resilience and urban-rural integration to promote coordinated regional development and rural revitalization is a complex endeavor requiring interdisciplinary and multi-angle analysis. While this study reveals the interactive relationship and dynamic trends between ecological resilience and urban-rural integration from a macro perspective, it is only an initial step. Subsequent work should focus on scientifically analyzing these concepts from a micro perspective and accurately predicting their evolving characteristics using multi-source data, offering valuable insights for regions across China and other developing areas worldwide.

5 Conclusion

This research systematically examines the synergy level between ecological resilience and rural-urban integration across 31 provinces in China from 2011 to 2022, exploring the distribution of ecological resilience and urban-rural integration levels, their spatiotemporal coupling coordination patterns, and forecasting future trends from 2023 to 2030. The study employs a comprehensive methodological framework, including the Synergy Degree Model to quantify coupling coordination, Kernel Density Estimation to analyze spatial distribution and variability, Long Short-Term Memory Network to forecast future synergy levels based on historical data, and Panel Vector Autoregression to examine the dynamic interactions between ecological resilience and urban-rural integration.

Key findings reveal that urban-rural integration levels generally exceed those of ecological resilience, with ecological resilience exhibiting greater variability—Xizang has the highest ecological resilience level, while Liaoning has the lowest. Temporally, the synergy level shows an overall increasing trend, with data tending to concentrate, though not significantly. Spatially, Guangdong exhibits the largest change in coupling coordination, while Hainan shows the smallest; Xizang has the highest coupling coordination, while Gansu has the lowest. Based on LSTM forecasts, the synergy between ecological resilience and rural-urban development is expected to show a fluctuating upward trend from 2023 to 2030, with most provinces transitioning from near imbalance or barely coordinated stages to primary or intermediate coordination after 2026. Dynamic interaction analysis reveals that, at the national level, ecological resilience and rural-urban development significantly influence each other, while regional analyses show varying effects: urban-rural integration notably impacts ecological resilience in the eastern region, ecological resilience significantly affects itself in the central and northeastern regions, and no significant interactions are observed in the western region.

The findings provide valuable insights for policymakers aiming to promote sustainable urban-rural development, highlighting the importance of ecological red lines and compensation mechanisms, and offering a framework applicable to other developing countries facing similar challenges of urbanization and ecological degradation. However, the study primarily focuses on human factors, with limited consideration of natural factors such as climate change and biodiversity loss, and its data are constrained to China, which may limit the generalizability of the findings. Future research should incorporate natural factors, conduct micro-level analyses, expand to cross-regional and cross-country comparisons, and utilize multi-source data, such as remote sensing, socio-economic surveys, and ecological modeling, to enhance the accuracy and depth of analysis.

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

YW: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. MS: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. SZ: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. ZJ: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. ZZ: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, 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.

Generative AI statement

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

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Supplementary material

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