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Research on the coupling coordination and prediction of industrial convergence and ecological environment in rural of China

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Coordination of rural industrial convergence and ecological environment is an important issue in rural social and economic development. This study aims to introduce a comprehensive evaluation index system and construct an integrated approach to evaluate and predict the coupling coordination between rural industrial convergence and ecological environment. Firstly, an index system including 40 indexes is developed for evaluating the two subsystems, and then entropy weight method is applied to determine the weights. Finally, a coupling coordination model and a grey prediction model are developed using provincial panel data from 2017 to 2021 for 29 provinces in China. There are three main findings: 1) penetration of new technologies and agricultural industrialization are the main driving factors of rural industrial convergence. In the three dimensions of ecological environment, environmental pressure has been the smallest contributor, implying that environmental pressure in rural China still needs attention in the next decade. 2) the coupling coordination between rural industrial convergence and ecological environment shows a fluctuating upward trend in China during the studied period and will continue to rise in the next 12 years. Among the 29 provinces studied, only 4 eastern developed provinces have reached primary coordination. The forecast data suggests that coordination with ecological environment will promote the development of rural industrial convergence. 3) the spatial differences of the coupling coordination are related to the level of economic and cultural development, application of agricultural technology, convergence of information technology, energy consumption structure and stock of natural resources. In conclusion, the research develops a rational index system and an effective approach to measure and predict the coupling coordination between rural industrial convergence and ecological environment, providing a theoretical basis for the environmental considerations in the rural industrial convergence policy-making.

KEYWORDS

rural industrial convergence, rural ecological environment, coupling coordination degree model, grey prediction model, ecological enironment

1. Introduction

China's agriculture has undergone two important changes. The first one is to deepen the whole industrial chain from single production to processing, circulation, sales, and brand building of agricultural products. The second is to transform the single production function to the multi-functions of leisure, tourism, ecology, culture, creativity, health care, etc. Since 2015, the central government of China has annually issued relevant documents and policies to promote the rural industrial convergence. All provinces and cities regard industrial convergence as an important means to accelerate the rural development and has achieved remarkable results.

However, rural industrial convergence will inevitably affect the ecological environment, which has attracted the attention of some scholars. Taking the integration of primary and tertiary industries in rural areas as an example, rural tourism has driven the improvement of rural infrastructure, created employment opportunities, and increased farmers' income. But, the blind expansion of low-level farmhouses and lack of relevant legislation have caused huge challenges to the rural ecological environment and affected the sustainable development of rural tourism. Yang and Li (2019) demonstrates that rural tourism enterprise's community participation has a positive impact on its environmental behavior. The environmental concerns of entrepreneurs and the consumption level of local rural residents moderate the relationship positively and negatively, respectively. The conclusion provides reference for the policy formulation of the environmental pollution behavior of farmhouses (Yang and Li, 2019). Zheng et al. (2021) believe that the benign interaction between rural living environment and rural tourism is important to rural revitalization. The rural living environment significantly promotes the development of rural tourism nationwide, which shows a "Matthew effect" (Zheng et al., 2021).

In addition, industrial development has also increased the difficulty of rural environmental remediation. The transfer of industrial and urban pollution to rural areas makes rural environment being destroyed. The massive use of chemical fertilizer and feed makes it more difficult to recycle human and livestock manure (Liu et al., 2008). Improper application of pesticides will lead to soil pollution by heavy metals, and excessive pesticide residues in agricultural products will lead to the reduction of biodiversity. The rapid development of rural e-commerce and express delivery services has produced a large amount of plastic packaging waste, which is randomly discarded in the living space (Liu and Huang, 2014). Landfill of plastic wastes in small garbage sites is easy to cause groundwater pollution, while incineration will produce much more harmful gas (Wang, 2019). Environmental issues have been paid more and more attention by management decision makers. For a long time, China's environmental protection design has mainly focused on industrial production and urban areas. Rural environmental governance has always been neglected, which hindered the development of rural areas in China.

Industrial prosperity is the cornerstone of the China's rural revitalization strategy, and the development of modern agriculture is an important part of industrial prosperity. Agricultural industrialization integrates the production, processing, packaging, transportation, storage, and sales of agricultural products, and is the process of realizing the extension of the agricultural chain and the modernization of agriculture. Rural industrial convergence is an upgraded version of agricultural industrialization, which is prominently reflected in richer business innovation, blurred industrial boundaries, interrelated benefit, diversified business entities, and richer functions. The integrated development of rural industries pays more attention to agricultural multi-functionality such as ecological protection, cultural inheritance, leisure tourism, health care and education, which promotes the development of circular agriculture, leisure agriculture, ecological agriculture, agricultural culture, creative agriculture, smart agriculture, e-commerce agriculture and other new formats. Rural industrial convergence is conducive to reducing the dependence of agricultural production on natural resources, relying more on technology and knowledge input, and improving sustainability of the agriculture.

Coordination of rural industrial convergence and ecological environment is the guarantee of rural revitalization and rural economic development. However, due to the availability of rural data, the relevant empirical research is still insufficient on this topic. Furthermore, the current research on the relationship between rural industrial convergence and ecological environment is mostly conducted from one aspect of industrial convergence, rather than the overall integration of primary, secondary and tertiary industries in rural areas. Based on literature review and theoretical analysis, this paper aims to: 1) construct a more comprehensive evaluation index system of rural industrial convergence and ecological environment quality. 2) develop a coupling coordination degree model and a grey prediction model using provincial panel data of 29 provinces in China from 2017 to 2021, to measure and predict the development of rural industrial convergence, the quality of ecological environment, and the coupling coordination between the two. 3) analyze spatial and temporal heterogeneity of the results, and the relationship between rural industrial convergence and ecological environment. Through the three targets above, the paper hopes to provide a new insight into the sustainable development of industrial convergence and ecological environment in rural areas.

2. Literature review

2.1 Industrial convergence

The division of labor theory of Marx and Marshall laid the foundation for the development of the theory of industrial convergence. Marx proposed that the development of handicrafts in workshops led to the creation of division of labor, and the combination of new departments generated by division of labor and the original handicrafts would produce new industries (Rosdolsky, 1977). Marshall (1992) also proposed in “Principles of Economics” that the refinement of the division of labor has led to the continuous narrowing of the boundaries between various industries (Marshall, 1992). In the middle and second half of the 20th century, many studies on industrial convergence appeared, initially focusing on the computer, printing, and broadcasting industries, and then extending to the fields of machinery, technology, and agriculture. Nicholas (1975) pointed out that the intersection of the three industries is a new field generated by fusion, and it is also the field with the fastest growth and largest number of innovations (Nicholas, 1975). Sahal (1985) believes that industrial convergence begins with the technological connection between industries (Sahal, 1985). Dosi (1988) believes that technology convergence is the wide application and diffusion of some technologies in a series of industries, which leads to innovation (Dosi, 1988). Technological convergence has changed the product form and value creation process of different industries, triggering the academic research on industrial convergence. With the development of practice, the research on industrial convergence has gradually expanded from the perspective of technology to the perspective of products, industries, and markets. The European Commission believes that industrial convergence is the convergence of three levels of technology, industry, service, and market (European Commission, 1997). Greenstein and Khanna (1997) think that industrial convergence is the shrinking or disappearing of industrial boundaries in order to adapt to industrial growth (Greenstein and Khanna, 1997). Yoffie (1996) defines industrial convergence as “the integration of independent products” based on the product perspective (Yoffie, 1996). Uekusa believes that technological innovation and deregulation have lowered barriers to industrial entry, which are the fundamental reasons for industrial convergence. Deregulation stimulates technological innovation and business model innovation, and expands market boundaries (Bronfenbrenner, 1977).

2.2 Rural industrial convergence

Western scholars’ research on rural industrial convergence is more carried out from the perspective of agricultural industrialization. Boehlje et al. (1998) believes that agricultural industrialization is an orderly chain composed of a series of business entities such as production materials supplying, food processing, retailing and so on (Boehlje et al., 1998). Rhodes (1993) believes that agriculture is not an isolated sector, and agricultural industrialization refers to the production and management activities carried out by specialized workers in specialized facilities in a specialized way (Rhodes, 1993). Knutson and Cropp (2013) points out that cooperatives form new organizational forms and improve competitiveness through social capital intervention (Knutson and Cropp, 2013). C. N., verdouw (2010) points out that the agricultural industry chain can relate to information technology to adapt to changing potential needs through reverse integration (Verdouw et al., 2010). Hjalager (1996) believes that convergence is based on the multi-function of agriculture, which can expand the scope of agricultural business (Hjalager, 1996). Hegarty (2005) believes that resource endowments and market conditions in different regions are the sources of agricultural diversity, and the potential they generate is huge (Hegarty and Przezborska, 2005). Davies (1992) believes that different farm operators play different roles in the market and affect their market position when entering the supply chain (Davies and Gilbert, 1992). McGehee (2004) believes that farms are a better carrier for developing rural tourism and leisure agriculture (Mcgehee and Kim, 2004).

Asian scholars pay more attention to the convergence of primary, secondary and tertiary industries in rural areas. Naraomi proposed that in order to increase the added value of agricultural products and farmers’ income, agriculture must be diversified, not only to develop planting and aquaculture, but also to focus on secondary and tertiary industries such as agricultural product processing, distribution, sales, and tourism. He emphasizes on the close connection between the three industries and the fundamental role of agriculture as a primary industry. Based on this, the concept of “sixth industrialization” of agriculture was put forward (Nagao and Iwasaki, 2010). Nakano (2014) (Nakano, 2014) and Itamura (2018) (Itamura et al., 2018) analyzed the development of the “sixth industrialization” of agriculture in Japan. Kim (2013) planned the development of six secondary industries in South Korea through horizontal and vertical diversification and convergence of agriculture and other industries (Kim, 2013). Uekusa (1989) pointed out that the integration of primary, secondary and tertiary industries can extend the industrial chain, realize the integration of production and sales, and allow farmers to obtain profits from secondary and tertiary industries (Uekusa, 1989). Research Group of the Department of Agriculture and Economics in China (2016) believe that the integrated development of rural primary, secondary and tertiary industries is based on agriculture, guided by new business entities, and linked by interests. Through agricultural industrialization, diversification, and technology penetration, it promotes the integration of agricultural production, processing, circulation, sale and tourism, and finally realizes agricultural modernization and farmers' income increase (National Development and Reform Commission macro institute and the Department ofagricultural economics research group, 2016).

2.3 Rural ecological environment

Rural pollution is one of the reasons for environmental deterioration. The US Environmental Protection Agency (EPA) found that agricultural non-point source pollution is the main cause of water quality damage in rivers and lakes. Related studies in Denmark, Japan, and the Netherlands also found that agricultural non-point source pollution has become the main source of water pollution (Dosi and Moretto, 1994; Yang and Zhu, 1999). In 2010, China's first census of pollution sources showed that the main pollutants discharged by agricultural pollution sources have exceeded industrial and domestic sources, becoming the first pollution source in China. Liang (2013) conducted a study on the pressure of China's rural ecological environment from 1990 to 2006 and found that the pressure on the rural ecological environment was gradually increasing, and the sources were regional heterogeneity. The higher the degree of intensification, the greater the pressure on the rural ecological environment (Liang, 2013).

Some scholars believe that the unreasonable development mode is a cause of rural ecological deterioration and environmental pollution. Technological progress can achieve economic development through resource substitution and recycling. Research by Grossman and Krueger (1995) shows that, technological progress can effectively suppress pollution in general, and only some technologies have negative effects of environmental pollution (Grossman and Krueger, 1995). Under the premise of unchanged technical conditions and industrial structure, the amount of agricultural pollution emissions depends on its economic scale (Rothman, 1998). Zheng (2002) believes that the urban-rural economic gap is the essential cause of pollution transfer. Although it is economically efficient, it does not meet the requirements of sustainable development and morality (Zheng, 2002). Hou (2004) believes that the extensive rural industry dominated by small and medium-sized enterprises aggravated rural pollution, and the rural environment needs to be improved by upgrading the rural industrial structure (Hou, 2004). Li (2005) believes that the main reasons for rural environmental problems are inefficient economic growth, unreasonable industrial structure, and industrial layout (Li, 2005). Hou et al. (2012) studied the impact of farmers' business behaviors on the rural ecological environment, and the finding demonstrates that farmers' business behaviors had a significant impact on agricultural non-point source pollution, water pollution and domestic waste pollution (Hou et al., 2012). Shen and Liu (2016) believe that the different interest and motivation of stakeholders have caused the realistic dilemma of rural environmental pollution (Shen and Liu, 2016).

2.4 Coordinated development of industrial convergence and ecological environment in rural area

Rural Industrial convergence and the rural ecological environment influence each other and are closely related. Some scholars have studied the impact of agricultural industrialization, agricultural diversification, and new technology penetration on the rural ecological environment. Chaniotakis (2017) points out that the function of agricultural industrial organizations is not only to provide raw materials for food processing, but also to play a positive role in agricultural commercialization, local economic development, stable employment, poverty alleviation, and ecological protection (Chaniotakis, 2017). Ge and Zhou (2011) believed that the development of agricultural economy and the increase in the proportion of aquaculture and cash crops would increase agricultural non-point source pollution, and technological progress had a significant inhibitory effect on agricultural pollution (Ge and Zhou, 2011). Xiong (2012) believes that rural tourism can improve the environmental protection awareness of tourism enterprises, community residents and tourists (Xiong, 2012), and Huang (2019) believes that rural tourism has transformed the rural ecological environment from "public goods" to "market goods", prompting farmers to consciously maintain and improve rural ecological environment (Huang, 2019). Some scholars believe that if the development of rural tourism exceeds the local capacity, it may cause damage to the ecological environment (Thompson, 2004; Tang et al., 2017).

Conversely, the ecological environment influences rural industrial convergence as well. Miller (2001) (Miller, 2001), Byeong (2009) (Lee and Kim, 2009) and Choi (2006) (Choi and Sirakaya, 2006) found that environmental sustainability affects the development of rural tourism through empirical research in the United States and South Korea. Enjoying the rural scenery and breathing fresh air is an important reason for tourists to choose rural tourism. Lewis et al. (2019) believes that seeking natural experiences and maintaining health are major motivations for senior travelers (Lewis and D'Alessandro 2019). The quality of the ecological environment is the basis for the development of agricultural multi-functions such as rural tourism, leisure agriculture, ecological agriculture, organic planting, green farming, health care research, etc. It is also the advantage of attracting investment, human capital, technology, and other advanced elements. A good ecological environment requires agriculture to reduce fossil energy consumption, adopt environmental technology, improve agricultural intensification, and develop new industries.

2.5 Commentary on the literature

According to literature analysis above, current research on the relationship between rural industrial convergence and ecological environment is mostly carried out from a certain aspect of rural industrial convergence, such as the convergence of primary and tertiary industries or the convergence of primary and secondary industries. These studies lay a foundation for exploring the complex interaction between rural industrial convergence and ecological environment. However, there are still few studies on the relationship between the overall integration of primary, secondary and tertiary industries and the ecological environment in rural areas, which is the focus of this study. In general, the previous research on the evaluation of rural industrial convergence can be improved in the design of the index system. Constrained by the availability of data and the difficulty of sorting, most existing studies use national, river basin or individual city data, rather than provincial panel data. There are few studies on the evaluation of rural ecological environment. Therefore, this study intends to build a more comprehensive index system for the evaluation of rural industrial convergence and ecological environment, and develop an integrated approach to measure and predict the development of the rural industrial convergence, the quality of rural ecological environment, and the coupling coordination between the two. This is not only a supplement to current research, but also provides a basis for policy formulation for the coordinated development of rural industrial convergence and ecological environment in various regions.

3. Methodology

3.1 Coupling coordination degree method

3.1.1 Coupling coordination model

In this paper, the coupling coordination degree (CCD) model is used to measure the coordinated development level between the industrial convergence and ecological environment in rural areas. The CCD model is often used to measure the relationship between different systems such as resources, ecology, economy, and society (Ariken et al., 2021; Yang et al., 2021; Xing et al., 2019). The CCD model uses the coupling degree to explain the relationship between the subsystems, and the coordinated development degree to comprehensively evaluate the whole system.

Assuming that U_i is the value of the ith subsystem, $i = 1, 2 \cdots n$,n is the number of subsystems, the formula for calculating the coupling degree c is:

$$c = \left[\frac{\prod_{i=1}^{n} U_i}{\left(\frac{1}{n} \sum_{i=1}^{n} U_i \right)^n} \right]^{\frac{1}{n}} \tag{1}$$

The distribution interval of U_i is $[0, 1]$, so the interval of C value is $[0, 1]$. The larger the C value, the higher the coupling degree between subsystems. The coupling coordination degree D is calculated as follows:

$$T = \sum_{i=1}^{n} \alpha_i \times U_{i,} \sum_{i=1}^{n} \alpha_i = 1 \tag{2}$$

$$D = \sqrt{C \times T} \tag{3}$$

where α_i is the weight of the ith subsystem,

It is generally assumed that subsystems have the same importance, so in this study set $\alpha_1 = \alpha_2 = 1/2$. The level of coordinated development is defined according to the D value, as shown in Table 1.

3.1.2 Evaluation index system

To evaluate the coupling coordination of industrial convergence and ecological environment in rural areas, we must first construct the evaluation index system for the two subsystems. Most of the indexes in the evaluation system are selected from the previous studies by statistic technique (Cao et al., 2010; Feng et al., 2016; Li et al., 2017; Wang et al., 2017; Li and Ran, 2019; Chen et al., 2021; Tan and Yao, 2021; Xu et al., 2021). However, there are also some new indexes coming from newly formulated polices. For instance, the data on agricultural diversification is very few and the indexes of "number of rural tourism demonstration counties" and "agricultural cultural heritage" are adopted according to government's new policy documents. Besides, the index of "Agricultural aircraft operating area proportion" in the dimension of "penetration of new technologies" is selected by the newly updated data from China Agricultural Machinery Industry Yearbook, as well as the indexes of "Proportion of water-saving irrigation area of farmland machinery" and "Proportion of mechanized straw back to the field" in the dimension of "rural ecological environmental response system".

The Evaluation index system of rural industrial convergence is composed of 2 first-level indicators, 5 secondary indicators and 22 tertiary indicators, including agricultural industrialization, agricultural diversification, penetration of new technologies, farmers' income increase and employment, and Urban-rural integration, as listed in Table 2.

The Pressure-State-Response Model (PSR) model has been widely used in the evaluation of environment and ecological security (Deschner et al., 2002). The PSR model is a theoretical framework developed by the United Nations Economic Cooperation Development Agency (OECD) and the United Nations Environment Programme (UNEP) to study environmental issues (Bai and Tang, 2010). It includes three subsystems: stress, state, and response. The model emphasizes the interaction between human activities and the natural environment, that is, after human activities exert a certain

TABLE 1 Division standard of coordinated development degree.

D value	(0, 0.1)	(0.1, 0.2)	(0.2, 0.3)	(0.3, 0.4)	(0.4, 0.5)	(0.5, 0.6)	(0.6, 0.7)	(0.7, 0.8)	(0.8, 0.9)	[(0.9, 1]
level	Extreme disorder	Severely disorder	Moderately disorder	Mild disorder	On the verge of disorder	Barely coordinated	Primary coordination	Intermediate coordination	Well coordinated	Quality coordination

TABLE 2 Rural industrial convergence development evaluation index system.

First -level indicator	Secondary indicator	Tertiary indicators	Direction	Weights
The mode of rural industrial convegence	agricultural industrialization	Proportion of service area of agricultural machinery professional cooperatives	+	0.0551
		Post-harvest processing mechanical power levels	+	0.0554
		The level of power machinery for primary processing of agricultural products	+	0.0399
		Per capita investment in fixed assets in agriculture, forestry, animal husbandry and fishery of rural households	+	0.0433
		Proportion of added value of agriculture, forestry, animal husbandry and fishery services	+	0.0260
	Agricultural diversification	Proportion of annual income of leisure agriculture	+	0.0580
		The percentage of facility agriculture area	+	0.0651
		Number of rural tourism demonstration counties	+	0.0167
		rural cultural heritage	+	0.0292
		Per capita grain output	+	0.0363
	Penetration of new technologies	Agricultural machinery productivity	+	0.0437
		Agricultural aircraft operating area proportion	+	0.0651
		The number of broadband per capita	+	0.0317
		Rural e-commerce development	+	0.1618
		The proportion of rural delivery lines	+	0.0068
		Rural R & D funding intensity	+	0.1199
The socio-economic effects of rural industrial convergence	Farmers' Income Increase and Employment	Rural residents' per capita disposable income	+	0.0402
		Rural residents' wage and property income proportion	+	0.0278
		Rural residents per capita fixed asset investment	+	0.0278
	Urban-rural integration	The proportion of agricultural expenditures in fiscal expenditure	+	0.0169
		The ratio of the per capita disposable income of urban and rural residents	-	0.0165
		The ratio of per capita consumption expenditure of urban and rural residents	–	0.0168

pressure on the environment, the environment will change its original state, and human beings will take action to improve the environmental quality according to the new environmental state. Based on the PSR model, an evaluation index system of rural ecological environmental quality including 3 first-level indicators and 18 secondary indicators is constructed, as listed in Table 3.

3.1.3 Data collection

The panel data used in the study are mainly collected from China Agricultural statistical yearbook, China Agricultural Machinery Industry Yearbook, China Leisure Agriculture Yearbook, China Agricultural Yearbook, and China Statistical Yearbook from 2017 to 2021. The research objects included 29 provinces of China, excluding Hong Kong, Macao and

TABLE 3 Rural ecological environment quality evaluation index system.

First -level indicator	Secondary indicator	Direction	Weights
Rural ecological environmental pressure system	Rural per capita electricity consumption	-	0.0125
	Agricultural unit area water consumption	_	0.0149
	Agricultural diesel use intensity	_	0.0096
	Agricultural fertilizer application intensity	_	0.0289
	Pesticide use intensity	_	0.0186
	Agricultural plastic film use intensity	_	0.0131
Rural ecological environmental state system	Proportion of disaster area of crops	_	0.0181
	Proportion of Nature Reserve Area	+	0.0679
	Reservoir capacity per capita	+	0.0988
	The area of farmland per capita	+	0.1184
	Proportion of effective irrigation area	+	0.0605
	percent of sanitary toilets	+	0.0405
Rural ecological environmental response system	Soil erosion treatment area proportion	+	0.0500
	Proportion of artificial afforestation area	+	0.0854
	Proportion of water-saving irrigation area of farmland machinery	+	0.0795
	Proportion of mechanized straw back to the field	+	0.0649
	Per capita solar water heater use	+	0.1137
	Per capita biogas pool gas production	+	0.1047

Taiwan regions. Tibet and Shanghai were not included in this study due to lack of data.

3.1.4 Entropy weight method

Entropy weight method (EWM) is used to determine the weight of evaluation index system. EWM refers to the concept of physics and is an objective weighting method (Kumar et al., 2021) which is widely used in decision making and evaluation studies (Malekinezhadet al., 2021; Zhu et al., 2020). Entropy is the degree of disorderly system, and the degree of discreteness of the index can be judged by entropy value. The higher the degree of discrete of the indicator, the smaller the information entropy, and the greater the weight of the indicator. Compared with the subjective weighting methods such as Analytic Hierarchy Process (AHP) and Delphi law, the calculation results of the EWM are only based on the original statistics of the indicator, which can reduce the subjective deviation caused by the human factors. The calculation steps of the EWM are as follows. Suppose there are m evaluation indicators and n evaluation objects, k indicating the period of evaluation data. The evaluation matrix in the kth year is listed as follows, $a_{ijk}$is the evaluation data of jthindicator of ithevaluation object in the kth year.

$$X_k = \begin{pmatrix} a_{11k} & \cdots & a_{1mk} \\ \vdots & \ddots & \vdots \\ a_{n1k} & \cdots & a_{nmk} \end{pmatrix} \quad (4)$$

The first step is to standardize the data, the normalization method of positive indicators and negative indicators is shown in formulas (5) and formulas (6).

$$r_{ijk} = \frac{a_{ijk} - \underset{i}{Min}\left(a_{ijk}\right)}{\underset{i}{Max}\left(a_{ijk}\right) - \underset{i}{Min}\left(a_{ijk}\right)} \quad (5)$$

$$r_{ijk} = \frac{\underset{i}{Max}\left(a_{ijk}\right) - a_{ijk}}{\underset{i}{Max}\left(a_{ijk}\right) - \underset{i}{Min}\left(a_{ijk}\right)} \quad (6)$$

Step 2, calculate the proportion of the ith evaluation object under jth indicator in the kth year

$$p_{ijk} = \frac{r_{ijk}}{\sum_{i=1}^{n} r_{ijk}},\ i = 1, 2, \cdots, n$$

Step 3, calculate the information entropy e_{jk}

$$e_{jk} = -\frac{1}{\ln n}\sum_{i=1}^{n} p_{ijk} \ln\left(p_{ijk}\right),\ j = 1, 2, \cdots, m \quad (7)$$

Step 4, calculate calculate the entropy w_j of each indicator

$$d_{jk} = 1 - e_{jk} \quad (8)$$

$$w_j = \frac{1}{t}\sum_{k=1}^{t} \frac{d_{jk}}{\sum_{j=1}^{m} d_{jk}} \quad (9)$$

TABLE 4 Evaluation and ranking of China's rural industrial convergence in 2017–2021.

Provinces in China	Agricultural industrialization		Agricultural diversification		Penetration of new technologies		Farmers' income increase and employment		Urban-rural integration		Total score	
	Score	Ranking	Score	Ranking	Score	Ranking	Score	Ranking	Score	Ranking	Score	Ranking
Beijing	0.0653	11	0.1043	1	0.1230	6	0.0751	2	0.0169	28	0.3847	4
Tianjin	0.0523	16	0.0833	5	0.0581	12	0.0448	3	0.0218	22	0.2603	8
Hebei	0.0478	24	0.0531	11	0.0606	11	0.0276	13	0.0259	12	0.2150	15
Shanxi	0.0518	19	0.0385	21	0.0417	20	0.0273	14	0.0227	20	0.1820	23
Inner Mongolia	0.0453	27	0.0501	14	0.0177	29	0.0212	24	0.0311	2	0.1655	26
Liaoning	0.0659	10	0.0720	9	0.0429	19	0.0287	11	0.0189	27	0.2284	12
Jilin	0.0519	18	0.0533	10	0.0260	26	0.0239	19	0.0298	3	0.1849	22
Heilongjiang	0.0561	13	0.0507	13	0.0834	9	0.0198	25	0.0380	1	0.2479	9
Jiangsu	0.0966	1	0.0987	2	0.1582	4	0.0381	7	0.0246	16	0.4162	2
Zhejiang	0.0512	20	0.0981	3	0.2235	1	0.0805	1	0.0273	9	0.4807	1
Anhui	0.0475	25	0.0818	6	0.0437	18	0.0254	18	0.0285	4	0.2268	13
Fujian	0.0704	8	0.0365	24	0.1327	5	0.0394	4	0.0231	19	0.3022	6
Jiangxi	0.0375	29	0.0473	15	0.0513	15	0.0286	12	0.0265	11	0.1912	21
Shandong	0.0811	4	0.0778	8	0.1707	3	0.0382	5	0.0202	25	0.3880	3
Henan	0.0375	28	0.0374	23	0.0331	22	0.0213	23	0.0255	13	0.1548	28
Hubei	0.0544	14	0.0465	18	0.0574	13	0.0255	17	0.0279	6	0.2115	16
Hunan	0.0718	7	0.0515	12	0.0899	8	0.0319	10	0.0240	17	0.2691	7
Guangdong	0.0453	26	0.0225	28	0.1936	2	0.0326	9	0.0154	29	0.3095	5
Guangxi	0.0965	2	0.0306	25	0.0290	23	0.0267	15	0.0279	7	0.2107	17
Hainan	0.0504	21	0.0112	29	0.0654	10	0.0382	6	0.0265	10	0.1917	20
Chongqing	0.0487	23	0.0790	7	0.0346	21	0.0169	27	0.0195	26	0.1987	19
Sichuan	0.0521	17	0.0860	4	0.0534	14	0.0220	22	0.0275	8	0.2410	10
Guizhou	0.0838	3	0.0226	27	0.0223	28	0.0157	28	0.0235	18	0.1679	25
Yunnan	0.0496	22	0.0471	16	0.0244	27	0.0176	26	0.0213	23	0.1600	27
Shanxi	0.0747	5	0.0436	19	0.0440	17	0.0264	16	0.0202	24	0.2090	18
Gansu	0.0534	15	0.0403	20	0.0288	24	0.0054	29	0.0219	21	0.1497	29
Qinghai	0.0721	6	0.0278	26	0.0270	25	0.0238	20	0.0248	15	0.1755	24
Ningxia	0.0667	9	0.0466	17	0.0492	16	0.0354	8	0.0279	5	0.2257	14
Xinjiang	0.0597	12	0.0379	22	0.0905	7	0.0228	21	0.0248	14	0.2357	11

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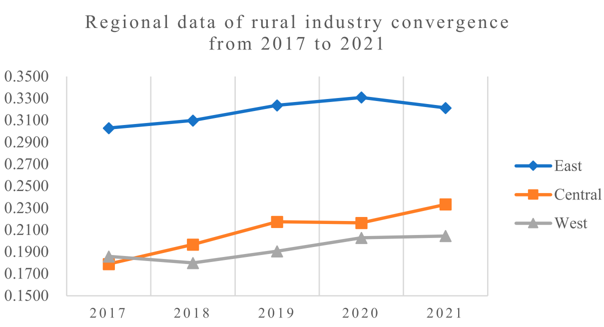

FIGURE 1
Comparison of the rural industrial convergence of different regions in China from 2017 to 2021.

The final step, calculate the composite score of *ith* evaluation object in the *k*th year

$$S_{ik} = \sum_{j=1}^{m} w_j r_{ijk} \tag{10}$$

3.2 Grey prediction model GM (1, 1)

The characteristic of grey prediction is that the model does not use the original data sequence, but the generated data sequence. Grey model is a method of modeling by accumulating the original data to generate data with approximate exponential law (Hu, 2020; Shih et al., 2011). The advantage of grey prediction is that the amount of data required is relatively small. It can make full use of the essence of the differential equation system. The calculation accuracy is relatively high (Akay and Atak, 2007).

GM (1.1) indicates that the model is a gray model containing a first -level differential.

Equation containing 1 variable. Define reference data columns:

$$x^{(0)} = \left(x^{(0)}(1), x^{(0)}(2), \cdots x^{(0)}(n)\right),$$

Generate data column $x^{(1)}$ by accumulation:

$$\begin{aligned} x^{(1)} &= \left(x^{(1)}(1), x^{(1)}(2), \cdots x^{(1)}(n)\right) \\ &= \left(x^{(0)}(1), x^{(0)}(1) + x^{(0)}(2), \cdots, x^{(0)}(1) + \cdots + x^{(0)}(n)\right) \end{aligned} \tag{11}$$

Where $x^{(1)}(k) = \sum_{i=1}^{k} x^{(0)}(i), k = 1, 2\cdots, n.$

$z^{(1)}$is the mean generation sequence of $x^{(1)}$

$$z^{(1)} = \left(z^{(1)}(2), z^{(1)}(3), \cdots z^{(1)}(n)\right),$$

$$z^{(1)}(k) = 0.5x^{(1)}(k) + 0.5x^{(1)}(k-1), k = 2, 3, \cdots n \tag{12}$$

The grey differential equation is established as follows

$$x^{(0)}(k) + az^{(1)}(k) = b, k = 2, 3, \cdots, n, \tag{13}$$

The corresponding albino differential equation is

$$\frac{dx^{(1)}}{dt} + ax^{(1)}(t) = b \tag{14}$$

Let $u = [a, b]^T, Y = \left[x^{(0)}(2), x^{(0)}(3), \cdots, x^{(0)}(n)\right]^T,$

$$B = \begin{bmatrix} -z^{(1)}(2) & 1 \\ -z^{(1)}(3) & 1 \\ \vdots & \vdots \\ -z^{(1)}(n) & 1 \end{bmatrix}$$

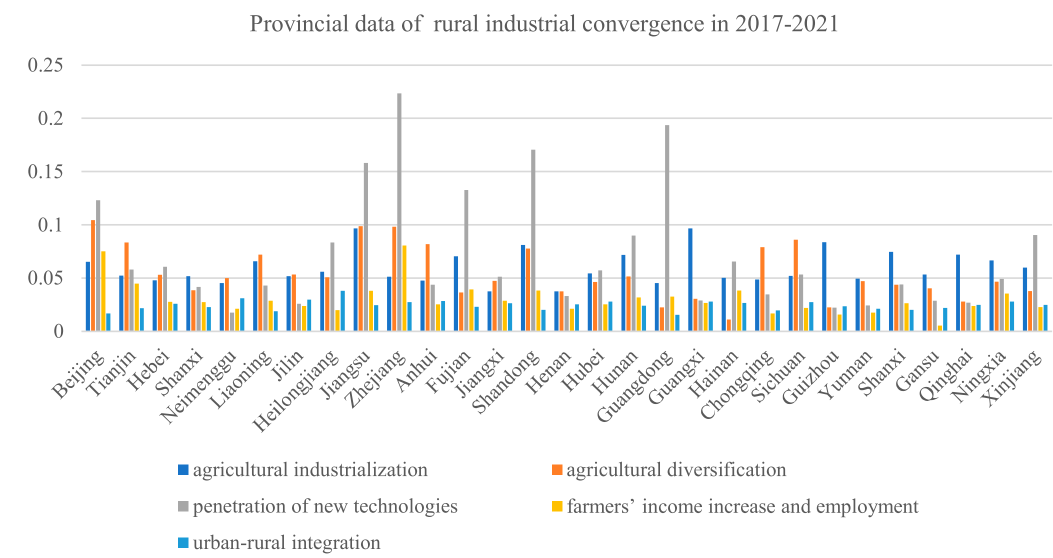

FIGURE 2
Data of rural industrial convergence by province in 2017–2021.

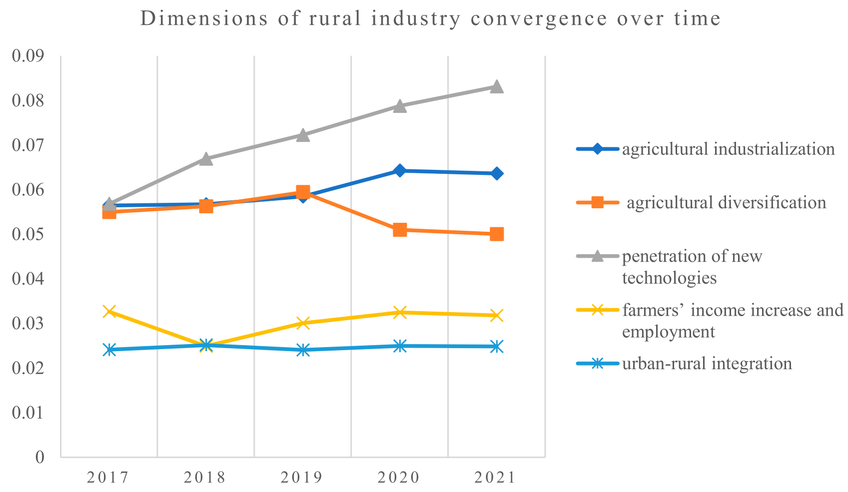

FIGURE 3
Trends of dimensions of rural industrial convergence over time from 2017 to 2021.

Then the estimated value of u that makes $J(u) = (Y - Bu)^T (Y - Bu)$ reach the minimum value by the least square method is

$$\hat{u} = \left[\hat{a}, \hat{b}\right]^T = \left(B^T B\right)^{-1} B^T Y$$

The solution of Equation 14 is

$$\hat{x}^{(1)}(k+1) = \left(x^{(0)}(1) - \frac{\hat{b}}{\hat{a}}\right) e^{-\hat{a}k} + \frac{\hat{b}}{\hat{a}}, k = 0, 1, \cdots n - 1 \cdots$$

In order to ensure the reliability of the model prediction, it is necessary to carry out residual test and posterior error test on the prediction results. The calculation formula of residual error $\epsilon(k)$ is:

$$\epsilon(k) = \frac{x^{(0)}(k) - \hat{x}^{(0)}(k)}{x^{(0)}(k)}, k = 1, 2, \cdots n \tag{15}$$

where$\hat{x}^{(0)}(1) = x^{(0)}(1)$, If $\epsilon(k) < 0.2$, it is considered acceptable, and if$\epsilon(k) < 0.1$,the accuracy is regarded high. The posterior error test is based on the two indicators of c (posterior error) and p (small error probability), Let the variance of the original sequence and the residual sequence be S_1^2 and S_2^2respectively,

$$S_1^2 = \frac{1}{n-1}\sum_{k=1}^{n}\left(x^{(0)}(k) - \bar{x}^{(0)}\right)^2 \tag{16}$$

$$S_2^2 = \frac{1}{n-1}\sum_{k=1}^{n}\left(\epsilon^{(0)}(k) - \bar{\epsilon}^{(0)}\right)^2 \tag{17}$$

$$c = S_2 / S_1,\ p = P\left\{0.6745 S_1 > \left|e^{(0)}(k) - \bar{e}^{(0)}\right|\right\} \tag{18}$$

When $c \le 0.35, p \ge 0.95$, the accuracy of the model is considered good.

4. Results and analysis

4.1 Evaluation of rural industrial convergence, ecological environment, and coupling coordination degree

4.1.1 Evaluation of rural industrial convergence

The weight of the evaluation index system for the rural industrial convergence is determined by the EWM and shown in Table 2. The scores and rankings of the development level of rural industrial convergence of 29 provinces in China from 2017 to 2021 are listed in Table 4. Nationwide, the level of rural industrial convergence is on the rise, with an average score of 0.2408, Zhejiang, Jiangsu, Shandong, Beijing, Guangdong, Fujian, Hunan, Tianjin and other eastern provinces are at the forefront, with an average score of 0.3177. The average score of the central region is higher than that of the west region, which are 0.2085 and 0.1927 respectively. The gap between the central and western regions is small, and the gap with the eastern region is obvious, as shown in Figure 1. The provincial data of rural industrial convergence from 2017 to 2021 is displayed in Figure 2.

By analyzing the scores of the sub dimensions of rural industrial convergence in Table 4, it is concluded that, the scores of each dimension from high to low are penetration of new technologies (0.0716), agricultural industrialization (0.0599), agricultural diversification (0.0543), farmers' income increase and employment (0.0304) and urban-rural integration

TABLE 5 The score and ranking of rural ecological environment quality in China in 2017–2021.

Provinces in China	Environmental pressure		Environmental state		Environmental response		Total score	
	Score	Ranking	Score	Ranking	Score	Ranking	Score	Ranking
Beijing	0.0346	28	0.1458	6	0.1863	4	0.3666	7
Tianjin	0.0711	21	0.1232	8	0.1848	5	0.3791	4
Hebei	0.0748	17	0.0751	24	0.2138	3	0.3637	8
Shanxi	0.0818	7	0.0631	27	0.1841	6	0.3291	15
Inner Mongolia	0.0866	5	0.1641	3	0.1349	17	0.3855	3
Liaoning	0.0698	22	0.1200	9	0.0970	26	0.2868	22
Jilin	0.0786	11	0.1578	4	0.1423	12	0.3788	6
Heilongjiang	0.0907	2	0.2139	2	0.0982	25	0.4028	2
Jiangsu	0.0594	23	0.0979	15	0.1678	10	0.3251	16
Zhejiang	0.0451	26	0.1110	11	0.1158	23	0.2718	25
Anhui	0.0776	12	0.0755	23	0.1544	11	0.3075	19
Fujian	0.0287	29	0.1017	14	0.0683	27	0.1987	28
Jiangxi	0.0815	8	0.0910	19	0.1396	14	0.3121	18
Shandong	0.0729	18	0.0922	18	0.2451	2	0.4102	1
Henan	0.0756	14	0.0717	25	0.1835	7	0.3309	13
Hubei	0.0756	15	0.1150	10	0.1708	9	0.3614	9
Hunan	0.0790	10	0.0760	22	0.1029	24	0.2579	26
Guangdong	0.0483	25	0.0891	20	0.0567	28	0.1941	29
Guangxi	0.0711	20	0.0926	17	0.1165	22	0.2803	23
Hainan	0.0350	27	0.0965	16	0.2473	1	0.3789	5
Chongqing	0.0859	6	0.0706	26	0.1408	13	0.2973	21
Sichuan	0.0867	4	0.1020	13	0.1251	20	0.3138	17
Guizhou	0.0945	1	0.0591	28	0.1235	21	0.2770	24
Yunnan	0.0809	9	0.0835	21	0.1385	15	0.3028	20
Shanxi	0.0719	19	0.0498	29	0.1349	16	0.2566	27
Gansu	0.0760	13	0.1242	7	0.1305	19	0.3307	14
Qinghai	0.0893	3	0.2193	1	0.0389	29	0.3476	11
Ningxia	0.0751	16	0.1047	12	0.1748	8	0.3546	10
Xinjiang	0.0580	24	0.1514	5	0.1342	18	0.3436	12

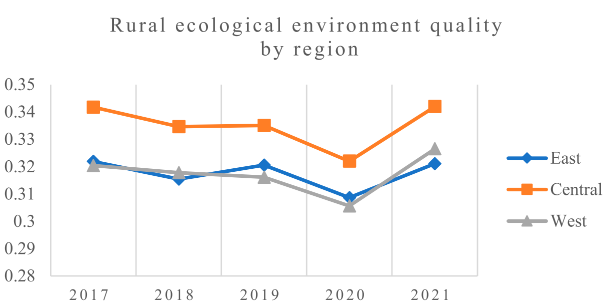

FIGURE 4
Comparison of rural ecological environment quality by region from 2017 to 2021.

(0.0246) respectively. Among these 5 dimensions, the penetration of new technologies and agricultural industrialization revealed an upward trend from 2017 to 2021, while the other three dimensions tended to be stable, as shown in Figure 3.

4.1.2 Evaluation of rural ecological environment quality

The weight of the evaluation index system for the rural ecological environment quality is calculated by the EWM and listed in Table 3. The scores and rankings of rural ecological environment quality of 29 provinces in China from 2017 to 2021 are listed in Table 5. Nationwide, the rural ecological environment quality has not changed much, with an average score of 0.3222. The score of the central region (0.3351) is

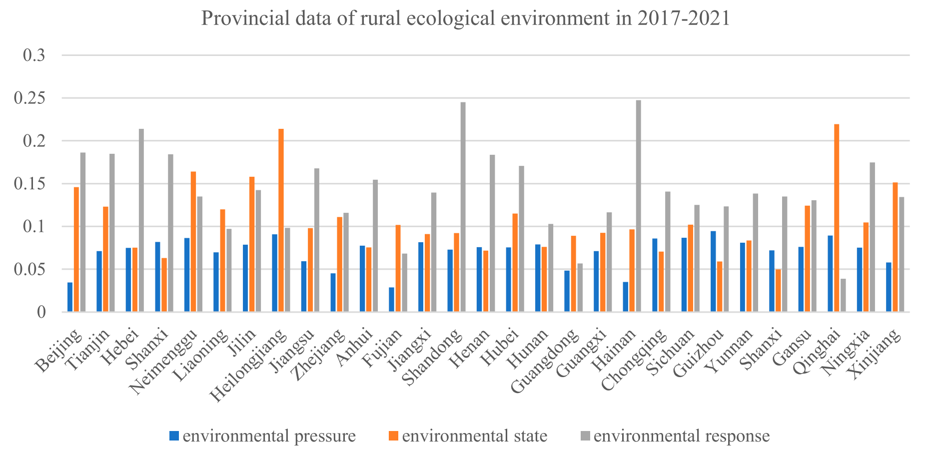

FIGURE 5
Rural ecological environment quality by province in 2017–2021.

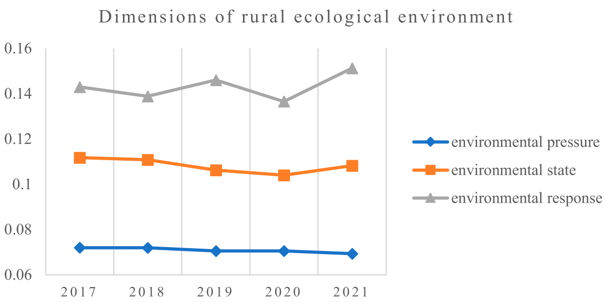

FIGURE 6
Dimension value of rural ecological environment from 2017 to 2021.

significantly better than that of the eastern (0.3175) and western regions (0.3173), and the gap between the eastern and western regions is small, as shown in Figure 4. The provincial data of rural ecological environment quality from 2017 to 2021 is displayed in Figure 5.

By analyzing the scores of the sub dimensions of rural ecological environment quality in Table 5, it is concluded that, the scores of each dimension from high to low are environmental.

Response (0.1431), environmental state (0.1082) and environmental pressure (0.0709) respectively. Among these 3 dimensions, environmental pressure and environmental state showed a slight downward trend from 2017 to 2021, and environmental response showed a fluctuating upward trend, as shown in Figure 6. This suggests that although the environmental pressure in rural areas of China is great, the humanistic response is increasing.

4.1.3 Evaluation of the coupling coordination between rural industrial convergence and ecological environment

The coupling coordination degree between rural industrial convergence and ecological environment in 2017–2021 are listed in Table 6. The mean value of the coupling coordination degree is 0.5206 nationwide, which means the two subsystems are Barely coordinated. Four provinces have achieved primary coordination, namely Shandong, Beijing, Jiangsu, and Zhejiang, all of which are developed coastal provinces in eastern China. Thirteen provinces have reached barely coordination, namely Heilongjiang, Tianjin, Xinjiang, Ningxia, Hebei, Hubei, Sichuan, Hainan, Jilin, Anhui, Hunan, Liaoning, and Inner Mongolia, most of which are provinces in central and Western China. The rest 12 provinces are on the verge of disorder, most of which are western provinces. The coupling coordination degree revealed a fluctuating upward trend from 2017 to 2021 in the whole country. Comparing the three major regions in China, eastern region has the highest coupling coordination (0.5551), followed by the central region (0.5110), and then the western region (0.4961). The gap between the East and the central and western regions is larger than that between the central and western regions, as shown in Figure 7.

4.2 Prediction results from grey model GM (1, 1)

GM (1.1) model is used to predict the development of rural industrial convergence, the quality of ecological environment and the coupling coordination between the two. Due to the large amount of data calculated, only the prediction data of

TABLE 6 Coupling coordination degree between rural industrial convergence and ecological environment of China in 2017–2021.

Provinces in China	2021	2020	2019	2018	2017	Mean	Level
Shandong	0.6228	0.6291	0.6512	0.6345	0.6170	0.6309	primary coordination
Beijing	0.6300	0.6036	0.5972	0.6022	0.6293	0.6125	primary coordination
Jiangsu	0.6210	0.6143	0.6249	0.5890	0.5794	0.6057	primary coordination
Zhejiang	0.6121	0.5983	0.6014	0.5983	0.5949	0.6010	primary coordination
Heilongjiang	0.5599	0.5607	0.5643	0.5679	0.5573	0.5620	barely coordinated
Tianjin	0.5585	0.5823	0.5715	0.5355	0.5492	0.5594	barely coordinated
Xinjiang	0.5493	0.5339	0.5237	0.5263	0.5320	0.5330	barely coordinated
Ningxia	0.5480	0.5297	0.5384	0.5261	0.5163	0.5317	barely coordinated
Hebei	0.5335	0.5235	0.5482	0.5168	0.5208	0.5285	barely coordinated
Hubei	0.5332	0.5317	0.5378	0.5165	0.5070	0.5252	barely coordinated
Sichuan	0.5143	0.5207	0.5288	0.5384	0.5189	0.5242	barely coordinated
Hainan	0.5102	0.5138	0.5134	0.5445	0.5118	0.5187	barely coordinated
Jilin	0.5133	0.5084	0.5126	0.5364	0.4989	0.5139	barely coordinated
Anhui	0.5270	0.5085	0.5150	0.5131	0.5034	0.5134	barely coordinated
Hunan	0.5593	0.5251	0.5167	0.4734	0.4781	0.5105	barely coordinated
Liaoning	0.4928	0.4932	0.5006	0.5114	0.5293	0.5055	barely coordinated
Inner Mongolia	0.5175	0.5046	0.5030	0.4915	0.4957	0.5025	barely coordinated
Qinghai	0.4978	0.5213	0.4932	0.4785	0.4922	0.4966	on the verge of disorder
Fujian	0.4924	0.4896	0.4900	0.4988	0.5040	0.4950	on the verge of disorder
Guangdong	0.5062	0.5127	0.4882	0.4886	0.4753	0.4942	on the verge of disorder
Shanxi	0.5089	0.4722	0.5105	0.4856	0.4937	0.4942	on the verge of disorder
Jiangxi	0.5158	0.5028	0.4989	0.4809	0.4702	0.4937	on the verge of disorder
Guangxi	0.5027	0.4993	0.4931	0.4865	0.4803	0.4924	on the verge of disorder
Chongqing	0.5091	0.5065	0.4889	0.4722	0.4851	0.4924	on the verge of disorder
Shanxi	0.4871	0.4874	0.4864	0.4650	0.4778	0.4807	on the verge of disorder
Henan	0.5026	0.4753	0.4809	0.4625	0.4551	0.4753	on the verge of disorder
Gansu	0.4870	0.4603	0.4661	0.4654	0.4790	0.4716	on the verge of disorder
Yunnan	0.4827	0.4625	0.4660	0.4508	0.4823	0.4689	on the verge of disorder
Guizhou	0.4805	0.4447	0.4471	0.4693	0.4770	0.4637	on the verge of disorder

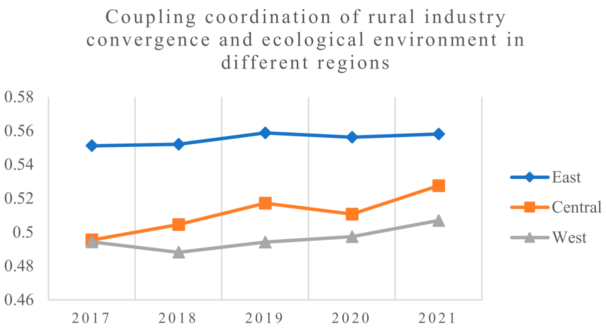

FIGURE 7
Comparison of the coupling coordination by region.

coupling coordination are shown, as listed in Table 7. The results of residual error test and posterior error test meet the accuracy requirements of mean relative error $\alpha < 0.01$ and posterior error $c \le 0.35$, $p \ge 0.95$. Parameter values of a, b, c and p are listed in Table 7. The coupling coordination between rural industrial convergence and ecological environment will increase steadily nationwide, from the value of 0.5142 in 2017 to value of 0.5866 in 2033. The rising speed of the central and western regions is relatively fast, while that of the eastern region is relatively slow, as depicted in Figure 8. By 2024, the central region is expected to exceed the overall level of the country, and surpass the eastern region in 2028. The western region is expected to surpass the eastern region in 2032.

This is mainly related to the urbanization rate of different regions. According to the 2021 statistical bulletin and public data released by each province of China, the urbanization rate of Shanghai, Beijing, Tianjin, Guangdong, Jiangsu, Liaoning, Zhejiang, and Chongqing has exceeded 70% in China, of which 7 provinces belong to the Eastern region and the rest one is a province-level municipality in the West. This means

TABLE 7 Grey prediction results of coupling coordination degree in the next 12 periods.

Year	Nationwide		Eastern China		Central China		Western China	
	Actual	Forecast	Actual	Forecast	Actual	Forecast	Actual	Forecast
2017	0.5142	0.5142	0.5511	0.5511	0.4955	0.4955	0.4942	0.4942
2018	0.5147	0.5155	0.5520	0.5539	0.5045	0.5056	0.4882	0.4877
2019	0.5227	0.5199	0.5587	0.5554	0.5171	0.5117	0.4941	0.4936
2020	0.5212	0.5244	0.5560	0.5569	0.5106	0.5180	0.4973	0.4996
2021	0.5302	0.5290	0.5580	0.5585	0.5275	0.5243	0.5069	0.5056
2022	—	0.5335	—	0.5600	—	0.5308	—	0.5116
2023	—	0.5382	—	0.5615	—	0.5373	—	0.5178
2024	—	0.5428	—	0.5631	—	0.5438	—	0.5240
2025	—	0.5475	—	0.5646	—	0.5505	—	0.5303
2026	—	0.5523	—	0.5662	—	0.5572	—	0.5367
2027	—	0.5571	—	0.5677	—	0.5640	—	0.5432
2028	—	0.5619	—	0.5693		0.5709	—	0.5497
2029	—	0.5667	—	0.5709	—	0.5779	—	0.5563
2030	—	0.5716	—	0.5724	—	0.5850	—	0.5630
2031	—	0.5766	—	0.5740	—	0.5921	—	0.5698
2032	—	0.5816	—	0.5756	—	0.5994	—	0.5766
2033	—	0.5866	—	0.5772	—	0.6067	—	0.5836
a	−0.0086		−0.0027		−0.0122		−0.0120	
b	0.5088		0.5516		0.4965		0.4789	
residual error test	α = 0.382%		α = 0.296%		α = 0.822%		α = 0.227%	
posterior error test	p = 1, c = 0.117		p = 0.936,c = 0.326		p = 1, c = 0.1611		p = 1, c = 0.040	

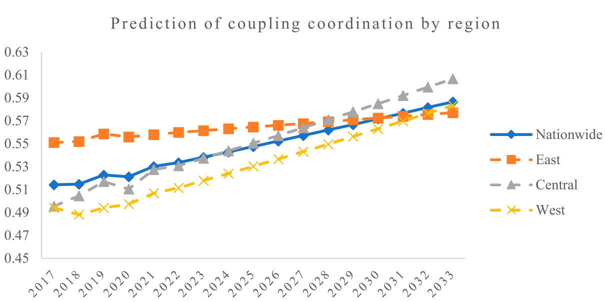

FIGURE 8
Prediction of coupling coordination by region.

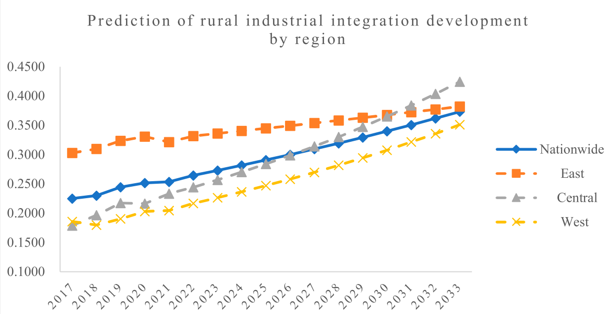

FIGURE 9
Prediction of rural industrial convergence development level by region.

that the potential of rural industrial convergence in central and western provinces of China, especially in terms of agricultural industrialization and penetration of new technologies, will be greater in the future. The central and western provinces have a large jurisdiction and have the possibility to improve the intensification of the primary industry and the integrity of the supply chain by cultivating new agricultural business entities. To improve resource utilization efficiency and the quality of the ecological environment, circular agriculture, high-tech agriculture and the combination of planting and breeding can be encouraged. The eastern region has developed industrial economy, a large population, and a much smaller agricultural land. Agricultural multifunctionality can be developed by transforming the traditional planting industry into a combination of modern agriculture, agritourism and

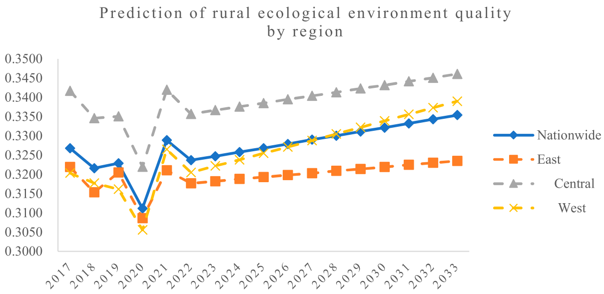

FIGURE 10
Prediction of rural ecological environment quality by region.

leisure agriculture. Deep processing of agricultural products and extension of the agricultural chain can be advocated to increase agricultural added value. Small-but-excellent agriculture is more likely to succeed by strengthening the interaction between rural and urban areas through urban agriculture and rural tourism, while reducing the environmental costs caused by non-intensive production.

Rural industrial convergence will increase steadily nationwide, from the value of 0.2251 in 2017 to 0.3732 in 2033, as shown in Figure 9. The speed is fastest in the central region, the second in the West and the slowest in the East. The central region will exceed the national average in 2027 and the eastern region in 2031. The gap between the West and the East is getting smaller and smaller. This implies that the coordination of rural industrial convergence and ecological environment may promote the development of rural industrial convergence. The quality of rural ecological environment will increase slowly nationwide after 2022, from the value of 0.3268 in 2017 to 0.3354 in 2033, as depicted in Figure 10. The environmental quality is the best in the central region, the second in the West and the worst in the East. In terms of the speed of environmental quality improvement, the West is the fastest, the central is the second, and the East is the slowest. This suggests that the quality of rural ecological environment may have a positive impact on the development of rural industrial convergence. The higher the quality of ecological environment and the faster the improvement speed, the more potential the development of industrial convergence.

5. Discussion

5.1 Establishment of the evaluation index system

This study is devoted to promote the understanding of the complex interaction between rural industrial convergence and ecological environment. An integrated approach is developed to explore the coupling coordination and prediction of rural industrial convergence and ecological environment. For the first step, a rational index system must be built to evaluate the two subsystems. In line with previous studies (Feng et al., 2016Li et al., 2017; Li and Ran, 2019; Chen et al., 2021; Tan and Yao, 2021), the indexes for rural industrial convergence are selected from two aspects: mode of rural industrial convergence and its socio-economic effects, which is furtherly subdivided into 5 dimensions of agricultural industrialization, agricultural diversification, penetration of new technologies, farmers' income increase and employment, and Urban-rural integration. Compared with previous research, this study used more direct indicators and has a higher degree of consistency with the theoretical research. It obtains more than 27,000 pieces of raw data from several statistical yearbooks and the newly data from government documents, ensuring the reliability of the research. From the evaluation result, the score of "penetration of new technologies" and "agricultural industrialization" is higher than "agricultural diversification". It is in accordance with the previous studies that agricultural industrialization is supported by new technology and rapid technological change (Lynne and Gary, 2010), which plays an important role in rural development (Urban, 1991). However, the agricultural industrialization has caused a problem in the sociology of agriculture and rural community welfare according to a study of 433 agriculture-dependent counties in the USA (Lyson and Welsh, 2005), hence the indexes of the socio-economic effects of rural industrial convergence are considered in this study. Farmers giving priority to traditional agriculture has hindered agricultural diversification into tourism in the EU (Hjalager, 1996), although demand for the different functions is significant from the case study of Spain (Kallas et al., 2010). Agricultural diversification is appealing to many countries since its benefits for increasing the farmers' income and preservation of rural heritage, however it still faces a lot of challenges (Hernandez-Mogollon et al., 2011). The index system for rural ecological environment is constructed by the theoretical framework of PSR drawing on previous research. The development of rural society and economy has put great pressure on the rural ecological environment, which has been widely concerned by scholars (Dufumier, 1992; Liu and Li, 2020). Most studies on assessment of rural ecological environment use the AHP method to build the evaluation system, which is a subjective weighting method (Xu et al., 2021; Yu, 2021). This study employs EWM, an objective weighting method, to assign weight, which can reduce the subjective deviation caused by the human factors. The evaluation results show that the environmental response is the greatest contributor to the environmental quality, while environmental pressure is the smallest.

5.2 Relationship between rural industrial convergence and ecological environment

The relationship between industrial convergence and ecological environment is discussed by scholars. Although the conclusion is controversial, most studies believe that industrial integration is beneficial to ecological environment through energy efficiency improving (Dong et al., 2021a), green innovation (Dong et al., 2021b) and industrial structure upgrading (Yang and Wang, 2022). With the convergence of high-tech technologies, some traditional industries have developed into new eco-friendly industries (Zhou et al., 2022). What about the situation in rural areas? This aroused our research interest. With the development of urbanization, many economic and social problems have emerged in China's rural areas, such as industrial decline, labor outflow, and left-behind children. In order to solve these problems, the Chinese government has formulated a national strategy of "the integration of rural primary, secondary and tertiary industries". This means that farmers can not only engage in production, but also engage in agribusiness, such as the processing, circulation and online sales of agricultural products, rural tourism, etc., which will improve the farmers' welfare and attract more entrepreneurs to rural areas. However, the primary development of industrial convergence and the lack of relevant legislation have caused negative impacts on the ecological environment in rural China. Therefore, it is urgent to explore the relationship between the two. Some scholars discussed the relationship between agricultural industrialization, agricultural diversification, rural tourism, and ecological environment (Hernandez-Mogollon et al., 2011; Davis and Langham, 1995) and found that interactions are complex. For example, while rural tourism can promote landscape protection and farmers' awareness of environmental preservation, it is easy to damage the fragile rural ecosystem. An integrated approach needs to be developed for further research. Fortunately, CCD model is an approach to measure the interaction among multiple complex systems. By establishing a CCD model and a grey prediction model, the coupling coordination of rural industrial convergence and ecological environment is measured and predicted for 29 provinces in China. The results suggest that rural industrial convergence and ecological environment are barely coordinated nationwide in 2017–2021 and will get better in the next decade. The four developed provinces in the eastern coastal area have reached primary coordination. Economic and cultural development, application of agricultural technology, convergence of information technology, energy consumption structure and stock of natural resources are the reasons for regional differences. The high quality of ecological environment and its coordination with rural industrial convergence will contribute to rural social and economic development.

5.3 Limitations and future research

This study uses panel data from 29 provinces in China from 2017 to 2021. Since the development of agricultural diversification in China is just at the initial stage, the data collection is difficult, so the time frame of the study is relatively short. The construction of the indicator system follows the scientific principle as much as possible, but some indicators may inevitably be missed. With the development of China's rural industrial convergence, relevant data will be more abundant, which provides a basis for exploring the relationship between rural industrial convergence and ecological environment in the future. The driving factors of the coupling coordination deserves further study.

6. Conclusion and suggestions

6.1 Conclusion

This paper constructs an integrated approach to explore the coupling and forecasting of rural industrial convergence and ecological environment. It first introduces a comprehensive evaluation index system of rural industrial convergence and ecological environment, and then uses EWM to determine the index weight and scoring of the two subsystems. Finally, a CCD model and a grey prediction model are developed to measure and predict the coupling coordination relationship. The finding suggests that:

1. The level of rural industrial convergence is on the rise nationwide from 2017 to 2021 and will remain the trend in the next 12 years. The speed is fastest in the central region, followed by the West and the slowest in the East. Among the 5 dimensions, penetration of new technologies and agricultural industrialization showed an upward trend and are better than agricultural diversification.
2. The rural ecological environment quality has not changed much from 2017 to 2021 nationwide and will increase slowly after 2022. Among these 3 dimensions, environmental pressure and environmental status showed a slight downward trend, and environmental response showed a fluctuating upward trend. This demonstrates that although the environmental pressure in rural areas of China is great, the humanistic response is increasing.
3. The rural industrial convergence and ecological environment are barely coordinated nationwide in 2017–2021. The coupling coordination showed a fluctuating upward trend on a national scale. Comparing the three major regions in

China, eastern region has the highest coupling coordination, followed by the central region, and then the western region. The spatial differences are related to the level of economic and cultural development, application of agricultural technology, convergence of information technology, energy consumption structure and stock of natural resources.

4. The quality of rural ecological environment has a positive impact on the development of rural industrial convergence. The higher the quality of ecological environment and the faster the improvement speed, the more potential the development of industrial convergence. The coordination with ecological environment will promote the development rural industrial convergence.

6.2 Suggestions

To promote the coupling and coordination between rural industrial convergence and ecological environment, the following suggestions are put forward:

1) Develop agricultural science and technology, cultivate new varieties of agricultural products, introduce deep-processing and OEM enterprises of agricultural products, build characteristic industrial clusters and modern agricultural industrial parks, increase industrial concentration and scale effect, improve agricultural production capacity, and reduce the energy consumption. For example, in the West Coast new area of Qingdao City, Shandong Province, a new planting standard to cultivate blueberry clusters is adopted in order to achieve simultaneous ripening and long-time storage. The local blueberry processing plant can not only process blueberry juice and blueberry wine for farmers, but also provide packaging services. Therefore, it makes much easier for farmers to be only in charge of plantation and sales of blueberries and significantly increases profits of them. This practice is also well illustrated in the agricultural scientific research institution in Dezhou, Shandong Province. The research on the cultivation of a wide range of pepper varieties has increased the utilization rate of pepper raw materials by more than 15%. A combination of overall industrial chain development and technological innovation will ease the burden on natural environment imposed by agricultural development.
2) Promote the development of green agriculture and circular agriculture. Adhere to the combination of planting and breeding, make rational use of agricultural waste, and develop resource-saving agriculture. Reduce the use of chemical fertilizers and pesticides, facilitate large-scale breeding of livestock, poultry, and aquatic products, and seek solutions for serious problems in agricultural ecological environment. In the case of Urumqi County in Xinjiang Uygur Autonomous Region, the innovative "symbiosis of fish and vegetables" ecological cycle system has been introduced and an ecologically recycled system in which the excreta of fish in the water is natural organic fertilizer, absorbed by vegetables through the water circulation system, and then returned to the sedimentation and decomposition tank for recycling. Water conservation of the system can be very beneficial, reducing the use of water by 5–10% of traditional vegetable greenhouse. Xingqing District in Ningxia Hui Autonomous Region has developed the ecological agricultural system of "rice crab symbiosis". It uses crabs to loosen the soil, catch insects, weed, and fertilize the field with crab feces, while provides a safe and cool growth environment for crabs in rice fields to realize a win-win situation of economy and ecology.
3) Integrate the rural cultural industry and rural tourism, expand the cultural, leisure, ecological and educational functions of agriculture, and form an industrial chain integrating feeling local culture, tasting local food, and enjoying rural scenery, to promote the improvement of rural ecological environment. Relying on its profound cultural heritage, Kaicheng town in Anhui Province integrates the brands of "hometown of calligraphy" and "hometown of poetry", and relies on West Jiuhua Scenic Spot and surrounding rural scenery to promote the integration of cultural tourism and agricultural tourism. Sanbanqiao village in Hubei Province, is one of the production bases of Wachang rice, the "top ten famous rice in Hubei Province". Relying on the advantages of the rice industry, it has cultivated colorful rice and built characteristic homestays, and held a research activity themed "the growth of a grain of rice", forming an effective integration of characteristic industries and natural scenery.
4) Support all kinds of entities to build regional agricultural production service platforms, explore effective forms of agricultural socialized services, develop agricultural production services such as agricultural materials supply, outsourcing, threshing, drying, precooling, and storage, and adopt pollution prevention and control measures for emerging industries to carry out ecological restoration. Taidong Township in Heilongjiang Province is located at 47° north latitude, and the Songnen Plain runs through the whole territory. It has the unique advantage of developing organic food and dairy industry, and has organically transformed 15 ha of land that meets the conditions for scale operation, realizing the whole process trusteeship of agricultural production.
5) Strengthen the convergence of information technology and agriculture. Intelligent production management is of great significance to agricultural production, efficiency and safety. Rural areas can build smart agriculture platforms to realize real-time monitoring of agricultural information by using Internet of things, geographic information system and satellite remote sensing technology. The grape greenhouses in Miyun District of Beijing city are equipped with a variety of digital equipment, such as water and fertilizer integration system, plant

protection machine and insect situation monitor. The water management of seedling cultivation used to depend on subjective judgment. Now, the smart system uses sprinkler irrigation equipment to carry out the drip fertigation according to the fertilizer demand and improves the quality of seedling cultivation. The system can monitor the irrigation volume in a timely manner, and stop irrigation when the irrigation reaches the maximum water holding capacity of the substrate. This practice not only improves the utilization rate of water and fertilizer, but also reduces the use of fertilizer and the damage to environmental pollution, and ultimately generates great economic and ecological benefits.

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

Conceptualization, JiyZ; methodology, JiyZ; software, JiyZ; investigation, JinZ; resources, JinZ; data curation, JG; writing—original draft preparation, JG; writing—review and editing, JG; visualization, JG.

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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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