J. Geogr. Sci. 2023, 33(11): 2257-2277
DOI: https://doi.org/10.1007/s11442-023-2175-x

The spatial pattern of population-land-industry coupling coordinated development and its influencing factor detection in rural China

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Abstract: Exploring the coupling coordinated level of rural population-land-industry (PLI) and its underlying driving mechanism contributes to the scientific decision-making on rural sustainable development. This study assessed the coupling coordinated level of PLI based on an improved evaluation index system and then revealed the regional differentiation and driving mechanism in China's rural areas in 2020. The results showed that the rural PLI coupling coordinated degree was 0.4694, and thus was in the stage of approximate incoordination. In addition, China's rural PLI coupling coordinated degree formed a spatially heterogeneous pattern with high levels in the northeast, eastern and central regions, and the intragroup difference contributed more than 80% to the total difference. The rural PLI coupling coordinated level was influenced by the combined effects of rural kernel and peripheral systems, but the rural kernel system mostly determined the differentiation. In the future, rural areas should first exploit population quality improvement projects, land consolidation projects and industrial integration development strategies to promote benign mutual feedback of PLI. Second, driving factors should be comprehensively regulated by implementing a "one village, one product" strategy, breaking the urban-rural dual system, improving agricultural machinery subsidies policy, and promoting urban-rural integrated development.

Keywords: population-land-industry (PLI); coupling coordinated degree; geodetector; driving mechanism; rural development; China

1 Introduction

Rural decline has attracted widespread attention worldwide (Liu and Li, 2017b; Li *et al.*, 2019a). Rural areas in both developed countries and emerging market countries are experiencing or have experienced rapid population loss, a lack of employment opportunities, the

Received: 2023-02-10 **Accepted:** 2023-07-28
Foundation: National Natural Science Foundation of China, No.41931293, No.42293271
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disappearance of traditional culture, moral degradation, and a widening urban-rural gap (Wegren, 2016; Liu and Li, 2017b; Delazeri *et al*., 2022). China is the world's largest developing country, and its long-standing urban-rural dual structure based on the *hukou* system has led to serious inequalities in urban-rural status (Song and Li, 2014; Li *et al*., 2018; Zang *et al*., 2020), exacerbating the problems of inadequate rural development and unbalanced urban-rural development (Long and Liu, 2016). Especially since the beginning of the 21st century, the rapid nonagriculturalization of rural PLI in the context of the unprecedented rapid urbanization and industrialization has triggered "rural diseases" characterized by environmental pollution, hollowing of construction land, and aging/weakening of social subjects (Liu, 2018a), severely restricting rural sustainable development.

According to rural territorial system theory, population, land, and industry are the core elements of rural development (Yılmaz *et al*., 2010; Liu *et al*., 2019), and there are complex mutual feeding mechanisms and transmission paths among rural PLI (Li *et al*., 2022). The rural population supports steady regional development through agricultural production activities. Population numbers reflect the magnitude of human resources and environmental impact and affect land use intensity and industrial development scale. Rural villages with population exodus often induce marginal arable land abandonment, nongrain cultivation, and construction land nonoccupation (Liu *et al*., 2014). In addition, population loss leads to the decline of the smallholder production mode and reduces the vitality of rural nonagricultural industry development, but it also provides an opportunity to promote large-scale agricultural production and the development of new industrial formats such as rural tourism by reshaping the relationship between population and land. Land is the spatial carrier of resource elements, and land use structure reflects the characteristics of human production and industrial layout (Long and Qu, 2018). The scattered layout of homesteads hinders the concentrated residence of the rural population and thus results in the inefficient configuration of public service facilities. Land is also an important production resource, but idle homestead resources, unreasonable rural industrial land planning, and arable land fragmentation can hardly satisfy the needs of intensive management and the integrated development of agricultural primary, secondary and tertiary industries (Liu, 2018b). Therefore, land engineering, rational planning and efficient use have become inevitable requirements for benign mutual feedback between PLI (Liu and Wang, 2019; Ge and Lu, 2021; Long *et al*., 2022). Industry is vital to rural development. Rural areas with dilapidated industries are often characterized by low economic development levels, massive population outflow, and vast abandoned land. On the one hand, the prosperous development of rural industry needs the support of rural talent and reasonable land planning. On the other hand, rural industrial prosperity can promote the migration of talent from the city to the countryside and the efficient use of rural land (Li *et al*., 2019a). Essentially, rural decline is a vicious cycle of element mismatch, structural imbalance, and functional disorder within the rural territorial system (Liu *et al*., 2019; Zhou and Liu, 2022). Scientific regulation and effective vitality activation to boost rural PLI coupling coordinated development is a crucial way to realize rural revitalization from a declining trend (Liu, 2018a).

At present, research on PLI coupling coordinated development mainly focuses on the following two aspects. One is the evolution and transmission mechanism of rural PLI. Dong *et al*. (2022) established an index system and measured the development level of rural PLI. Ma *et al.* (2018) uncovered the transmission mechanism between population decline, industrial shift and rural land change in Pinggu district. Gao *et al.* (2020) revealed the coupling synergistic development pattern of land and industry in Xuzhou city. Shi and Wang (2021) and Liu *et al.* (2022) dissected the coupling status between the rural population and settlement land in the Yellow River Basin and a typical region of the Loess Plateau, respectively. The other is the evolutionary characteristics of rural PLI coupling coordinated development. Under rapid urbanization, the urban-rural transformation and nonagricultural transformation of PLI were measured in the Bohai Rim (Yang *et al.*, 2015), Beijing-Tianjin-Hebei region (Yang *et al.*, 2018) and Gansu province (Ma *et al.*, 2019). Other studies focused on rural development and analyzed the coupling state and temporal evolution characteristics of rural PLI in the Huang-Huai-Hai Plain (Cheng *et al.*, 2019), Loess Plateau (Huang *et al.*, 2021) and Shaanxi province (Niu and Du, 2021).

Generally, the current studies on rural PLI mainly focus on typical regions and lack national-scale analysis, making it difficult to clearly understand the pattern of rural PLI coupling coordinated development from a macro perspective. Second, many studies have been conducted from the aspect of transformation and factor development, but it is urgent to reveal the coupling coordinated development state and optimal regulation path of rural PLI in the context of rural revitalization strategy. Finally, most current studies focus on the spatio-temporal pattern analysis of the rural PLI coupling coordinated development level, so there is little research on the quantitative detection of driving factors.

Thus, the coupling coordinated development level of China's rural PLI in 2020 was comprehensively measured by using the coupling coordinated degree model and its spatial differentiation pattern was analyzed. Furthermore, based on rural development theory, the influence of the rural kernel system and rural peripheral system on rural PLI coupling coordinated development was also measured by utilizing the geodetector. Finally, this study elucidated the driving mechanism and proposed the optimal regulation path to realize the coupling coordinated development of rural PLI.

2 Materials and methods

2.1 Study area

There are very large regional differences in China. According to the division of the National Bureau of Statistics, China can be divided into overall four parts: the eastern region, northeast region, central region, and western region (http://www.stats.gov.cn/). In 2020, China's rural population, grain sown area and grain output were 510 million, 117 million hectares and 669 million tons, respectively. The gross output value of agriculture, forestry, animal husbandry and fishery reached 1.38 billion yuan, accounting for 13.56% of the total GDP. At the regional level, in 2020, the rural populations of the eastern, central, western and northeastern regions were 165 million, 150 million, 163 million and 32 million, respectively. The central region had the highest grain sown area and grain yield of 34 million hectares and 202 million tons respectively, while the northeast region had the lowest. The gross output values of agriculture, forestry, animal husbandry and fishery in the eastern, central, western and northeastern regions were 0.44 billion yuan, 0.36 billion yuan, 0.44 billion yuan and 0.14 billion yuan, respectively.

2.2 Evaluation index system of population-land-industry coupling coordinated development in rural China

By referring to the commonly used indicators of PLI in the study of rural territorial systems and combining them with data availability (Liu *et al*., 2019; Zhou *et al*., 2019; Lyu *et al*., 2022), this study constructed an evaluation index system as shown in Table 1.

Table 1 Evaluation index of the population-land-industry coupling coordinated development level in rural China

Index		Index meaning	Unit
Population	Rural permanent population (+)	Represents the level of rural human resources	10^4 people
	Proportion of rural population over 65 years old (–)	Represents the aging degree of rural population	%
	Average years of education of residents in the county (+)	Represents the quality of rural population	year
Land	Cultivated land area at the county level (+)	Represents the number of cultivated land resources	ha
	Rural residential land (–)	Represents the scale of rural residential land	ha
	The comprehensive production potential of farmland	Represents the quality level and production potential of farmland	kg/ha
Industry	Grain output at county level (+)	Represents rural grain output level	tons
	The output value of primary industry at the county level (+)	Represents the output benefit of rural resources	10^8 yuan

Note: "+" refers to a positive indicator, and "–" refers to a negative indicator.

The rural permanent population was selected to represent the abundance of rural population resources, and more population plays a positive role in promoting rural development under the background of continuous urbanization (Cheng *et al*., 2019). The proportion of the rural population over 65 years old was selected to reflect the degree of aging of the rural population, with older rural demographic characteristics hindering the efficient development of rural industry and land use (Ren *et al*., 2023). In addition to the quantitative and structural characteristics of the rural population, this study chose the average years of education of residents in the county to represent rural population quality (Li *et al*., 2015). The more educated rural residents are, the more likely they are to seize development opportunities and realize leapfrog development.

Cultivated land and residential land are two important land use forms in rural areas. The more abundant cultivated land resources imply a higher rural population carrying capacity and higher food production. Rural residential areas are places where rural populations live, and the coupling development of rural residential land and rural populations is an important basis for the coordinated development of rural PLI (Qu *et al*., 2021). However, in recent years, the rural hollowing problem has become prominent, so it was treated as a negative indicator (Huang *et al*., 2021). Land use has a dominant and recessive morphology, and the structural and quantitative characteristics of land use mentioned above belong to the dominant morphology (Long *et al*., 2020). In this study, farmland quality, a recessive morphology, was included in the index system and represented by the comprehensive production potential of farmland.

Grain production is a unique regional function of rural areas, and its yield scale is closely related to the amount of cultivated land, climatic conditions and farming patterns. In addition, the output value of the primary industry is a direct representation of the economic benefits of agriculture, forestry, animal husbandry and fishery output in rural areas. Therefore, grain output and the output value of the primary industry at the county level were selected to represent the development level of rural industry (Cheng *et al*., 2019).

2.3 Selected influencing factors of population-land-industry coupling coordinated development in rural China

The rural development system has a multifactor composition and a multilevel structure (Figure 1). It consists of the rural kernel system and the rural peripheral system, where the rural kernel system can be subdivided into the rural ontology system and the rural subject system (Zhang and Liu, 2008). The interaction effect of the rural kernel system and rural peripheral system directly determines whether the rural development system can operate sustainably, so it also affects the mutual feedback and coupling coordinated degree of PLI within the countryside. The rural ontology system is composed of natural resources, including land, water, climate, and various ecological environment elements, and belongs to a basic support system. The rural subject system includes socioeconomic factors, and the rural peripheral system mainly includes rural development policy, urbanization development stage, and the development model.

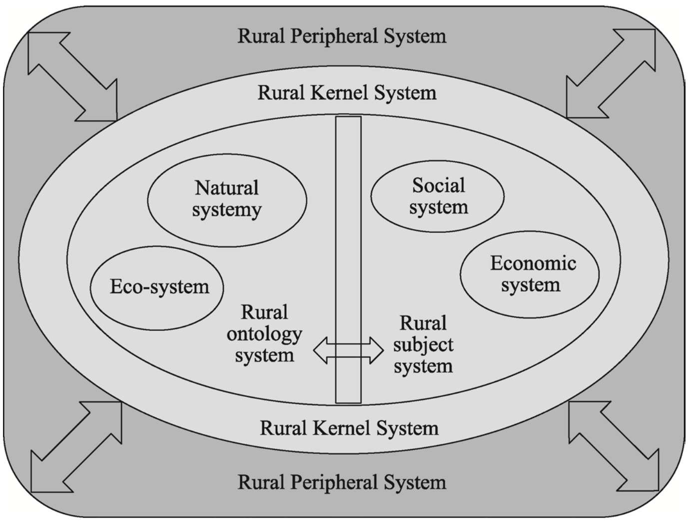

Figure 1 The hierarchical structure of the rural development system (Zhang and Liu, 2008)

According to the basic principles of the rural development system, an index system that drives the rural PLI coupling coordinated situation was constructed. In terms of the rural kernel system, this study selected China's agricultural resources and environment zoning data (*X*1), county average elevation (*X*2), and county terrain relief (*X*3) to measure the influence of the rural ontology system. In addition, due to limited data access, this study only chose county-level per capita GDP (*X*4) and county-level arable land per capita total power of agricultural machinery (*X*5) as socioeconomic factors in rural subject system. Besides, this study selected the county-level urbanization rate (*X*6) as a representative indicator of the rural peripheral system, and this was mainly based on the following two considerations. First, in China's rapid urbanization process, rural PLI has undergone dramatic changes, and urbanization has always been an important external driving force for rural changes (Long and Liu, 2016). Second, the urbanization level affects regional development policy and path selection (Fang *et al*., 2015) and it is easier to quantify.

2.4 Methodology

2.4.1 Coupling coordinated degree model

The coupling coordinated degree model is currently one of the main methods to study the interaction efficiency and coordination level of two or more systems (Fan *et al*., 2019; Yang *et al*., 2020). Here, this study used it to measure the coupling coordinated development level of PLI in rural China. The calculation steps are as follows:

(i) Standardization of index data

$$U_i = \left(X_i - \min(X_i)\right) / \left(\max(X_i) - \min(X_i)\right) \tag{1}$$

$$U_i = \left(\max(X_i) - X_i\right) / \left(\max(X_i) - \min(X_i)\right) \tag{2}$$

where U_i is the standardized index variable value; X_i is the original value of the index variable; and $\min(X_i)$ and $\max(X_i)$ are the minimum and maximum of the original value X_i respectively. If it is a positive indicator, it is processed by Formula (1), while if it is a negative indicator, it is processed by Formula (2).

(ii) Coupling degree of rural PLI

$$H_i = \sum_{j=1}^{n} W_j H_{ij};\ L_i = \sum_{j=1}^{n} W_j L_{ij};\ I_i = \sum_{j=1}^{n} W_j I_{ij};\ C_i = 3 \times (H_i \times L_i \times I_i)^{1/3} / (H_i + L_i + I_i) \tag{3}$$

where H_i, L_i, and I_i represent the scores of the population element, land element, and industrial element in the *i*th county, respectively; W_j represents the weight of the *j*th index, obtained by using the entropy weight method; and H_{ij}, L_{ij}, and I_{ij} represent the standardized data of the *j*th index of the population element, land element and industrial element in the *i*th county, respectively. C_i is the coupling degree of the PLI development level in the *i*th county, and its value belongs to [0,1]. In general, when $C_i = 0$, the rural PLI system is in an unrelated state; when $C_i \in (0, 0.3)$, the rural PLI system is in a low-level coupling stage; when $C_i \in [0.3, 0.5)$, the rural PLI system is in the antagonistic stage; when $C_i \in [0.5, 0.8)$, the rural PLI system is in the run-in stage; when $C_i \in [0.8, 1)$, the rural PLI system is in a high-level coupling stage; and when C = 1, the PLI system is in the benign resonance coupling stage.

(iii) Coupling coordinated degree of rural PLI

$$T_i = \alpha H_i + \beta L_i + \gamma I_i \tag{4}$$

$$D_i = \sqrt{C_i \times T_i} \tag{5}$$

where T_i is the comprehensive development score of the rural PLI system in the *i*th county, D_i is the coupling coordinated development score of the rural PLI system in the *i*th county, and α, β, and γ are undetermined coefficients. Based on previous studies, the undetermined coefficients are determined to be 1/3 (Yang *et al*., 2020). Generally, the degree of coordination can be divided into 10 types, as shown in Table 2 (Wang *et al*., 2015a).

Table 2 Classification of rural population-land-industry coupling coordinated degree

Coupling coordinated degree	Coupling coordination level	Coupling coordinated degree	Coupling coordination level
0.00≤D≤0.10	Extreme incoordination	0.50<D≤0.60	Approximate coordination
0.10<D≤0.20	Serious incoordination	0.60<D≤0.70	Primary coordination
0.20<D≤0.30	Moderate incoordination	0.70<D≤0.80	Intermediate coordination
0.30<D≤0.40	Mild incoordination	0.80<D≤0.90	Good coordination
0.40<D≤0.50	Approximate incoordination	0.90<D≤1.00	Superior coordination

2.4.2 Theil index

The Theil index can measure the degree of regional imbalance and has decomposition characteristics (Bourguignon, 1979; Shorrocks, 1980). This study employed it to analyze the spatial difference in rural PLI development levels in China. The specific calculation formula is as follows (Cui *et al.*, 2022):

$$T = \frac{1}{n}\sum_{i=1}^{n} y_i \ln(y_i) \tag{6}$$

$$T = \sum_{k=1}^{K} y_k \left(\sum_{i \in g_k} \frac{y_i}{y_k} \ln\left(\frac{y_i / y_k}{1/n_k} \right) \right) + \sum_{k=1}^{K} y_k \ln\left(\frac{y_k}{n_k / n} \right) = T_w + T_b \tag{7}$$

$$I_w = \frac{T_w}{T} \times 100\%;\ I_b = \frac{T_b}{T} \times 100\% \tag{8}$$

where T is the total development difference among counties in China, and T_w and T_b are the intragroup difference and intergroup difference after grouping respectively. k represents the kth group belonging to a county; g_k is the county contained in the kth group, and n_k is the number of counties in g_k. n is the total number of counties in this study; y_i represents the ratio of the development level of county i to the sum of the development level of the county in the whole study area, and y_k represents the ratio of the sum of the rural development level of all counties in the kth group to the sum of the development level of the county in the whole study area. In Formula (8), I_w and I_b refer to contribution rates of intragroup difference and intergroup difference to overall differences, respectively.

2.4.3 Geodetector

Geodetector is a spatial statistical tool used to detect the spatial differentiation of geographical phenomena and reveal the explanatory power of driving factors by using q statistics (Wang *et al.*, 2010). This study utilized single-factor detection, double-factor interaction detection, and ecological detection to analyze the decisive force of influencing factors on PLI coupling coordinated levels in rural China.

$$q = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N\sigma^2} = 1 - \frac{SSW}{SST} \tag{9}$$

where $h = 1, \ldots, L$ is the strata of variable Y or X, that is, classification or partition; N_h and N are the number of units in strata h and the whole region respectively. σ_h^2 and σ^2 are the variances of the Y values of strata h and the whole strata, respectively. SSW and SST are the sum of the variances within the strata and the total variance of the whole region respectively.

The value of q belongs to [0, 1], and the higher the value, the greater the explanatory power of independent variable X to attribute Y. A value of q equals to 1 indicates that variable X completely controls the spatial distribution of Y. A value of q equals to 0 indicates that variable X has no relationship with Y.

Double-factor interaction detection is mainly used to compare the sum of the contribution of two individual variables with the contribution of the two variables combined. Ecological detection is used to compare whether there are significant differences between variables in the spatial differentiation of Y (Wang *et al*., 2016).

2.5 Data source

The socioeconomic data used in this article including China's county-level population data, grain output, the output value of primary output, urbanization rate, per capita GDP, and total power of agricultural machinery, were mainly from China's County-level Statistical Yearbook 2021, and some of the data were derived from provincial and municipal statistical yearbooks or statistical bulletins. The data on the proportion of the rural population over 65 years old and the average years of education of residents were collected from the China Population Census Yearbook 2020. In addition, the data on national county zoning, cultivated land, rural residential land, the comprehensive production potential of farmland and DEM were obtained from the Center for Resource and Environmental Data Science, Chinese Academy of Sciences (https://www.resdc.cn/). China relief degree and agricultural resources and environment data partition data originated from the Global Change Research Data Publishing and Repository (http://geodoi.ac.cn/WebCn/Default.aspx). Given data limitations, a total of 1623 national county units were obtained in this study. In particular, the data of county units in Beijing, Shanghai, Tianjin, Hainan, Taiwan, Hong Kong, and Macao were completely missing in this study.

3 Results

3.1 Spatial pattern of the population-land-industry coupling coordinated development level in rural China

3.1.1 The population-land-industry development level

In 2020, the development levels of rural PLI in different regions differed greatly, showing regional heterogeneity (Figure 2). Overall, the development level of the population element was higher than that of the land element and industrial element. Specifically, the average development level of the population element in China was 0.2889, and 640 counties exceeded the average level, accounting for 39.43% of all counties studied. The proportion of counties at the low-development level (0.0–0.2) of the population element was 29.45%, and these were concentrated in the Changbai Mountain area, Loess Plateau, and western Sichuan Plateau. The proportion of counties at the high-development level (>0.4) of the population element was 18.73%, and these were concentrated in the Huang-Huai-Hai Plain, central Hunan, and Leizhou Peninsula. The average development level of land elements in China was 0.2348, and 41.28% of counties exceeded that. The proportions of counties at low-development level (0.0–0.2) and high-development level (>0.4) were 52.19% and

18.85%, respectively. The average level of rural industrial development in China was 0.1495, and 37.52% of counties exceeded the national average level, but 73.88% and 4.37% of counties were at low-development level (0–0.2) and high-development level (>0.4) of industrial elements, respectively. The high-value areas of land elements and industrial elements were both concentrated in the east of the Northeast China Plain and the Huang-Huai-Hai Plain. The average score of the rural PLI comprehensive development level was 0.2244 and 43.62% of the counties were above the average level. However, 49.60% of the counties were at the stage of low comprehensive development level (0–0.2) and only 8.93% of counties reached the high-development level (>0.4).

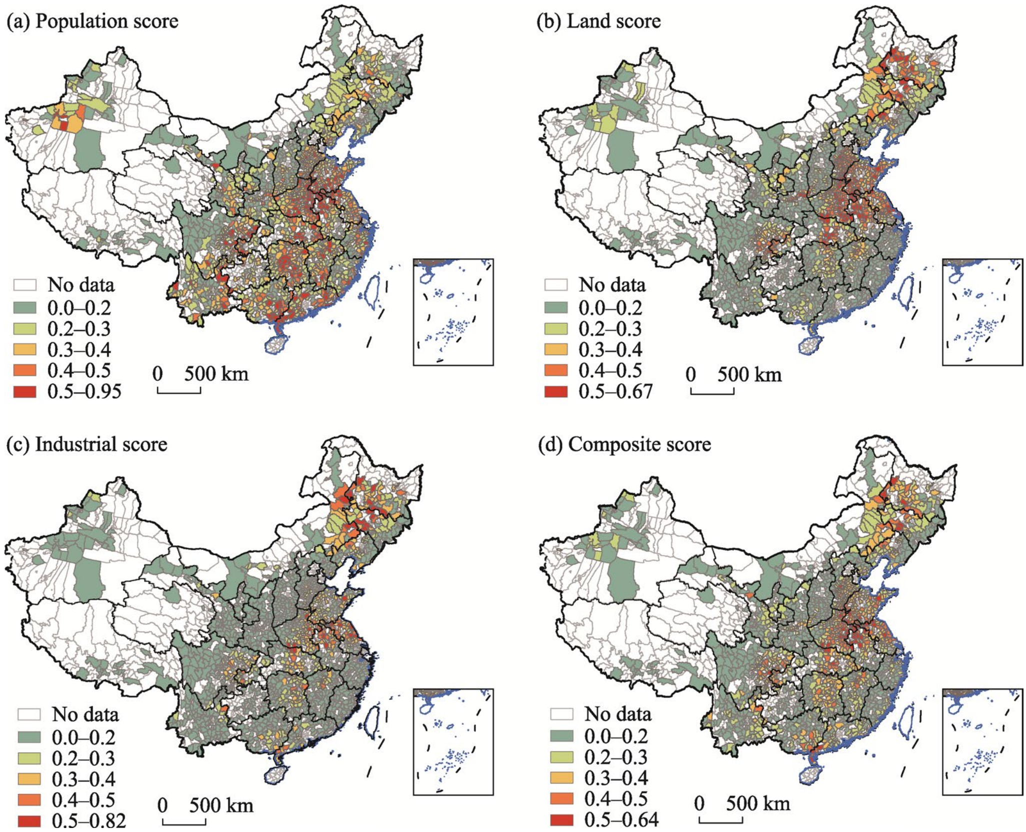

Figure 2 Each element and comprehensive development level of population-land-industry in rural China in 2020

3.1.2 The population-land-industry coupling degree and coupling coordinated degree

In 2020, the average coupling degree of PLI in rural China was 0.8881, reaching a high-level coupling stage (Figure 3). There were 0.49% of the counties in the antagonistic stage and 15.22% of the counties in the running-in stage. In contrast, more than 80% of the counties were in the high-level coupling stage, indicating that rural PLI development during this period was relatively synchronous. From the perspective of regional differentiation, the rural PLI coupling degree to the east of the Hu Huanyong Line was higher than that to the west. In 2020, the level of PLI coupling coordinated development in China's rural areas has had obvious spatial heterogeneity. The average of the national coupling coordinated development level was 0.4341, and this was in the stage of approximate incoordination. There were

2.40% of the counties in the stage of serious incoordination, 12.57% of the counties in the stage of moderate incoordination, 27.29% of the counties in the stage of mild incoordination, and 27.79% of the counties in the stage of approximate incoordination. The proportions of counties at the bare coordinated level, the primary coordinated level and the intermediate coordinated level were 19.10%, 8.63% and 2.22% respectively. Generally, the high-value areas of rural PLI coupling coordinated development were concentrated in the Northeast China Plain, Huang-Huai-Hai Plain, Sichuan Basin, and the middle reaches of the Yangtze River.

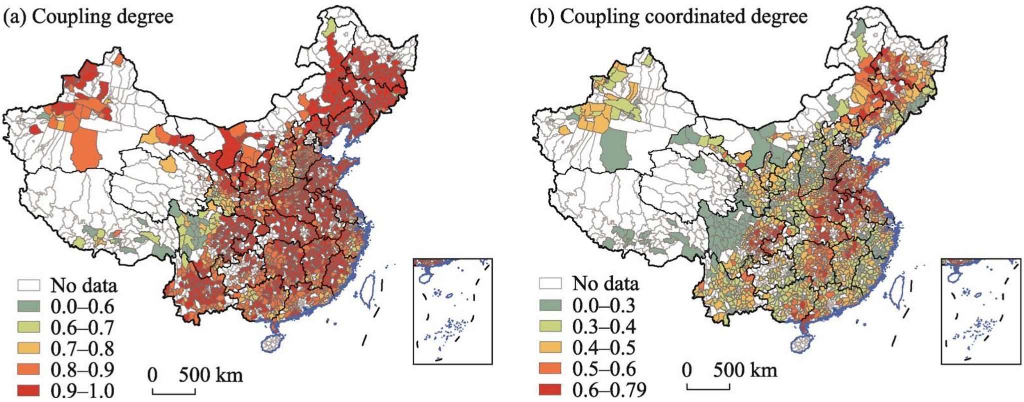

Figure 3 Spatial pattern of coupling degree and coupling coordinated degree of population-land-industry in rural China in 2020

3.2 Regional differences in the rural population-land-industry coupling coordinated development level in rural China

3.2.1 Differences between the four regions

In 2020, the comprehensive development level of rural PLI in the western region was lower than the national average, while the other regions were higher than the average (Table 3). The northeast region had higher scores in the land element and industrial element, and the eastern region had the highest score in the population element. In addition, the rural PLI coupling degree in the northeast region was the highest (0.9534), followed by the central region and eastern region. The rural PLI coupling degree in the western region was the lowest (0.8646), but the four regions were all in the high-level coupling stage. In 2020, the rural PLI coupling coordinated degree in the four regions was in the following order: northeast region > eastern region > central region > western region. The rural PLI coupling coordinated degree in the western region was in the mild incoordination stage, while the other regions were in the approximate incoordination stage.

In 2020, China's rural industrial development level had the largest difference (Table 3). The Theil index was 0.2937, much higher than the population element and land element. For each factor, Theil index decomposition results showed that the intragroup difference remained the main source of the overall difference with a contribution rate above 80%. Moreover, in terms of the population element and coupling coordinated degree, the intragroup difference between the four regions contributed more than 90%.

Table 3 Development level of each element of rural population-land-industry in different regions of China

	Population score	Land score	Industrial score	Composite score	Coupling degree	Coupling coordinated degree
Whole China	0.2889	0.2348	0.1495	0.2244	0.8881	0.4341
Eastern region	0.3249	0.2776	0.1628	0.2551	0.8909	0.4662
Central region	0.3218	0.2691	0.1626	0.2512	0.9000	0.4629
Western region	0.2509	0.1658	0.1082	0.1750	0.8646	0.3792
Northeast region	0.2158	0.2937	0.2630	0.2575	0.9534	0.4826
T	0.1154	0.1947	0.2937	0.1301	0.0434	0.0066
T_w	0.1057	0.1676	0.2594	0.1152	0.0385	0.0063
T_b	0.0097	0.0271	0.0343	0.0149	0.0049	0.0003
I_w	91.59%	86.08%	88.32%	88.55%	88.71%	95.45%
I_b	8.41%	13.92%	11.68%	11.45%	11.29%	4.55%

3.2.2 Provincial differences

The development results among different provinces showed that Henan had the highest score in the population element (0.4248) and composite score (0.3560), Shandong had the highest score in land element (0.4167), Heilongjiang had the highest score in the industrial element (0.3337), Chongqing had the highest score in the coupling degree (0.9711), and Jiangsu had the highest score in the coupling coordinated degree (0.5743) (Figure 4). Tibet scored the lowest development level in each dimension. Generally, the rural PLI coupling degree in Tibet was in the antagonistic stage, and Qinghai, Gansu, Ningxia, Shanxi, and Xinjiang were in the running-in stage, while the other provinces were in the high-level coupling stage. In addition, in terms of rural PLI coupling coordinated degree, Tibet was in the stage of serious incoordination and Qinghai was in the stage of moderate incoordination. Jiangsu, Henan, Shandong, Heilongjiang, Anhui, Chongqing and Hubei were in the stage of approximate coordination, while the other 19 provinces were in the stage of mild incoordination and approximate incoordination.

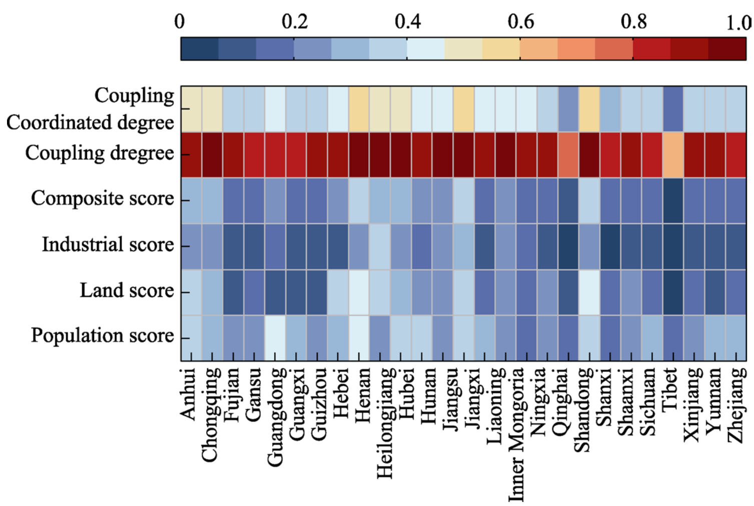

Figure 4 Development level of each element of rural population-land-industry in different provincial-level regions of China

3.3 Geodetection of the influencing factors of population-land-industry coupling coordinated development in rural China

3.3.1 Single-factor detection

The single-factor detection results showed that all the influencing factors of PLI coupling coordinated development in rural China passed the significance test of 5%, but the explanatory power differed significantly. On average, the explanatory power of the rural kernel system was 5.44 times greater than that of the rural peripheral system. Inside the rural kernel system, the explanatory power of the rural ontology system was 6.58 times greater than that of the rural subject system, indicating that the rural natural resource background mostly determined the rural PLI coupling coordinated development level (Table 4). Specifically, the order of explanatory power of each indicator was as follows: relief (*X*3)> elevation (*X*2)> agricultural resources and environmental factors (*X*1)> agricultural modernization level (*X*5)> urbanization level (*X*6)> economic development level (*X*4). County relief and elevation had the greatest influence on rural PLI coupling coordinated development, reaching 50.29% and 48.66% respectively. The explanatory power of agricultural resources and environmental factors reached 33.80%, while the other three factors alone accounted for less than 20%.

Table 4 q value and significance level of driving factors

	*X*1	*X*2	*X*3	*X*4	*X*5	*X*6
q statistic	0.3380	0.4866	0.5029	0.0160	0.1184	0.0537
p-value	0.0000	0.0000	0.0000	0.0189	0.0000	0.0000

3.3.2 Double-factor interaction detection

The double-factor interaction detection results showed that approximately half of the interaction detections were nonlinear enhancements (Table 5); that is, the joint interaction intensity of two individual factors was greater than that of two individual factors added together. The interaction between *X*1, *X*2, and *X*3 had a double-factor enhancement, while the interaction between *X*4, *X*5, and *X*6 had a double-factor nonlinear enhancement. Moreover, the explanatory force q values of $X1 \cap X4$ and $X1 \cap X6$ were 0.3971 and 0.4243 respectively, and the q values of $X2 \cap X4$ and $X3 \cap X4$ were both over 0.5, showing that the combined effect of the rural natural background and the socioeconomic development level as well as urbanization process could better explain the geographic pattern of rural PLI coupling coordinated development.

Table 5 Double-factor interaction detection results of driving factors

	*X*1	*X*2	*X*3	*X*4	*X*5	*X*6
*X*1	0.3380					
*X*2	0.5694	0.4866				
*X*3	0.5673	0.5256	0.5029			
*X*4	0.3971	0.5231	0.5340	0.0160		
*X*5	0.4177	0.5205	0.5358	0.1666	0.1184	
*X*6	0.4243	0.5357	0.5517	0.1106	0.2000	0.0537

Note: [yellow] Double-factor enhancement [orange] Double-factor nonlinear enhancement.

3.3.3 Ecological detection

A total of 86.67% of the influencing factors had a significant difference in explanatory power, while the other 13.33% had no significant difference in explanatory power according to ecological detection (Table 6). There were significant differences between *X*1 and all other indicators, and the explanatory power of *X*2 and *X*3 was significantly different from all other factors except each other. There was no significant explanatory difference between *X*4 and *X*6. However, the explanatory power between *X*4 and *X*5 as well as between *X*5 and *X*6 differed significantly. From a comprehensive perspective, the explanatory power of the rural ontology system was significantly differentiated from that of the rural subject system as well as the rural peripheral system, but the explanatory power of the rural subject system and the rural peripheral system had no significant difference.

Table 6 Ecological detection on influencing factors of rural population-land-industry coupling coordinated development level

	*X*1	*X*2	*X*3	*X*4	*X*5	*X*6
*X*1						
*X*2	Y					
*X*3	Y	N				
*X*4	Y	Y	Y			
*X*5	Y	Y	Y	Y		
*X*6	Y	Y	Y	N	Y	

Note: Y indicates that the explanatory power of the two factors is different at the significance level of 95%, while N has the opposite meaning.

4 Discussion

4.1 The driving mechanism of population-land-industry coupling coordinated development in rural areas

The rural territorial system is an open system with certain functions and structures (Liu *et al.*, 2019). Under the combined action of the push force of the rural kernel system and the pull force of the rural peripheral system, the rural PLI coupling coordinated level dynamically fluctuates (Figure 5). From the perspective of the rural kernel system, altitude and topographic relief reflect the redistribution effect of topographic conditions on rural water, gas, heat and other resource elements, affecting rural population magnitude, farmland fragmentation degree, grain production and industrial layout (Zhou *et al.*, 2019; 2020a). The abundance of agricultural resources comprehensively reflects the environment carrying capacity. Areas with higher carrying capacity tend to have a larger rural population, higher land utilization degree, and more grain production (Cheng *et al.*, 2016). Additionally, the economic development level and agricultural modernization affect the agricultural production efficiency and integrated development degree of rural industries, and thus influence the development vitality and coupling coordinated level of rural PLI. From the perspective of the rural peripheral system, along with China's socioeconomic transformation, the geographical space and element structure for rural production and living have undergone significant changes (Liu, 2018a). Rural areas are characterized by an aging population, left-behind population, hollowing out of village land, nonagricultural farmland and industrial depression, adversely affecting rural PLI coupling coordinated development (Long and Liu, 2016). From the analysis of the determining force, the rural ontology system provides basic support for rural development and mostly determines the rural PLI coupling coordinated state. The rural subject system and rural peripheral system can regulate the rural PLI coupling coordinated status but have relatively small determining power. The interaction driving force often presents a nonlinear enhancement effect, indicating that the rural PLI coupling coordinated development is influenced by a combination of influencing factors.

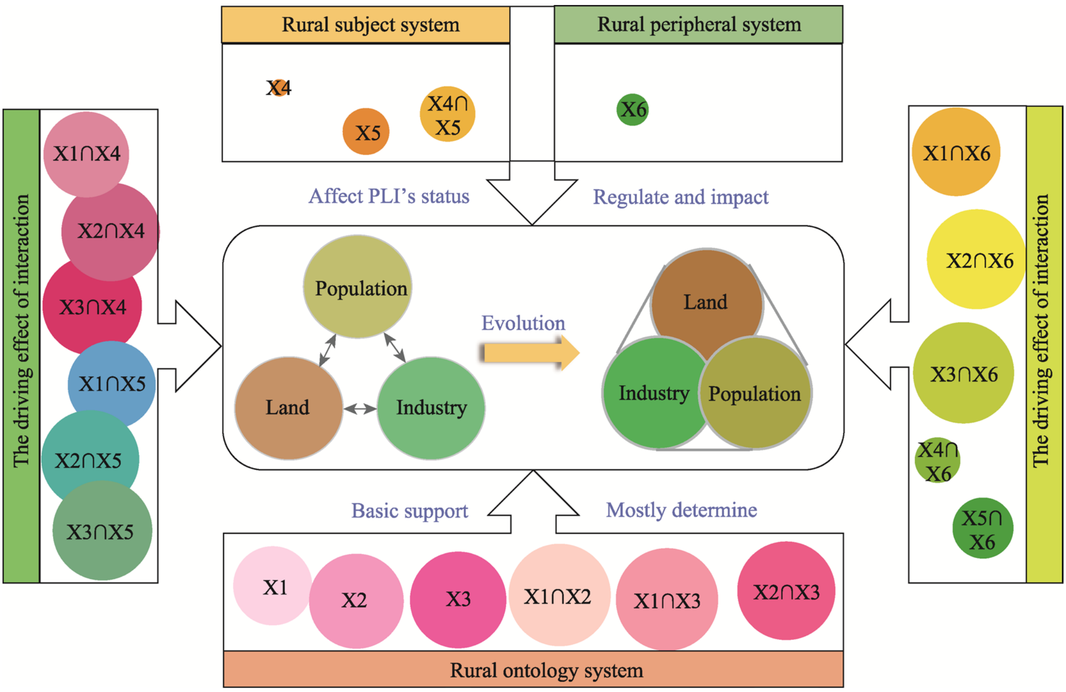

Figure 5 Driving mechanism of influencing factors of the coupling coordinated development of rural population-land-industry

Note: The area of the circle represents the magnitude of the determining force.

4.2 Policy implications of optimizing rural population-land-industry to promote rural sustainable development

4.2.1 Rural population-land-industry

There are complex interactions between PLI and they work together for rural development (Ma *et al.*, 2019). Adjusting the development level of PLI and its ratio structure through policy regulation can promote rural PLI coupling coordinated development and rural sustainable development.

With the continuous advancement of urbanization, urban areas have provided substantial employment opportunities and higher income levels than rural areas. The rural labor force left for urban areas and rural elites have also moved away from rural areas for further education or business opportunities. The proportion of women, children, and the elderly in the rural permanent population has increased; thus, the population structure is getting older and weaker. Meanwhile, rural aging has prompted the conversion of marginal arable land to orchards and forestry land as well as led to the abandonment of poor-quality cultivated land (Xie *et al*., 2022). On account of the *hukou* system, rural populations hardly settle in urban areas and access public services such as education, medical care, and elderly care (Zhang and Lu, 2018). Rural migrant workers have to bring their labor income back to the countryside and this abundant money is often spent to renovate old houses and build new houses, resulting in the prominent phenomenon of "multiple houses for one family". Meanwhile, with the gradual acceleration of the urbanization process, "rural people to leave the countryside and desert new houses" has caused a realistic paradox of population reduction and residential land increase (Liu *et al*., 2014). Furthermore, labor force loss and the decrease in comparative benefits of agricultural planting have reduced farmers' cultivation enthusiasm, and cultivated land fragmentation has limited large-scale and centralized management (Zheng *et al*., 2022). The lack of effective policy support and rural talent drive makes it difficult for rural industries to survive fierce market competition. In addition, the development of the rural internet also brings leisure tourism, e-commerce, and other opportunities, but rural areas can rarely turn potential opportunities into actual industries due to the lack of talented people (Li *et al*., 2019b). For the secondary and tertiary industries, villages and towns strictly control incremental construction land, and the rural stock construction land cannot be effectively converted into industrial land due to property rights and policy regulation, so the insufficient supply problem of industrial land is serious.

The mutual feedback transmission mechanism of rural PLI reinforces this vicious circle. However, spontaneous mutual feeding alone cannot drive the rural territorial system to migrate to the optimal state, and its internal force is less than the viscous binding force. Therefore, it is necessary to conduct policy intervention and control, namely, regulating mutual feeding (Li *et al*., 2022). In terms of population, the focus of policy adjustment is to strengthen the skills training required by farmers for large-scale production, encourage "three villagers" (entrepreneurs who go to the countryside, migrant workers who return to the countryside, college students who go back to the countryside) to play a greater role in rural construction, and give full play to their intellectual advantages to drive rural development (Liu, 2018a). In terms of land, the local government needs to strengthen land consolidation and high-standard farmland construction and create intensive rural living spaces and a centralized contiguous farmland production layout. Besides, it is necessary to encourage the transfer of farmland management rights, improve the homestead exit mechanism, and strictly limit the nonagricultural use of farmland (Long, 2014; Jiang *et al*., 2022). In terms of industry, first, it is vital to cultivate new agricultural business entities and facilitate large-scale production and management of arable land. Second, based on rural characteristic resources, new business forms such as agritainment and ecotourism should be developed, the agricultural industry chain should be extended, and the integrated development of rural industries should be promoted under the drive of rural talent (Liu *et al*., 2020). Rural leaders should also intensively utilize rural construction land and rationally plan rural industrial development to meet the land demand for new industrial forms.

Through the abovementioned policies and engineering measures, the driving effect of rural talent is remarkable, and thus can effectively explore rural distinctive resources to develop characteristic industries such as cultural tourism and farmhouse entertainment. Large-scale farmers or agricultural cooperatives can promote scaled production and standardized management of rural cultivated land, and effectively improve grain production capacity and grain crop planting benefits. As a result, the mutual feedback between PLI in rural areas will change from a vicious circle to a benign interaction, and the rural PLI coupling coordinated development level will significantly improve, which can effectively activate the endogenous power and sustainable development of the countryside (Figure 6).

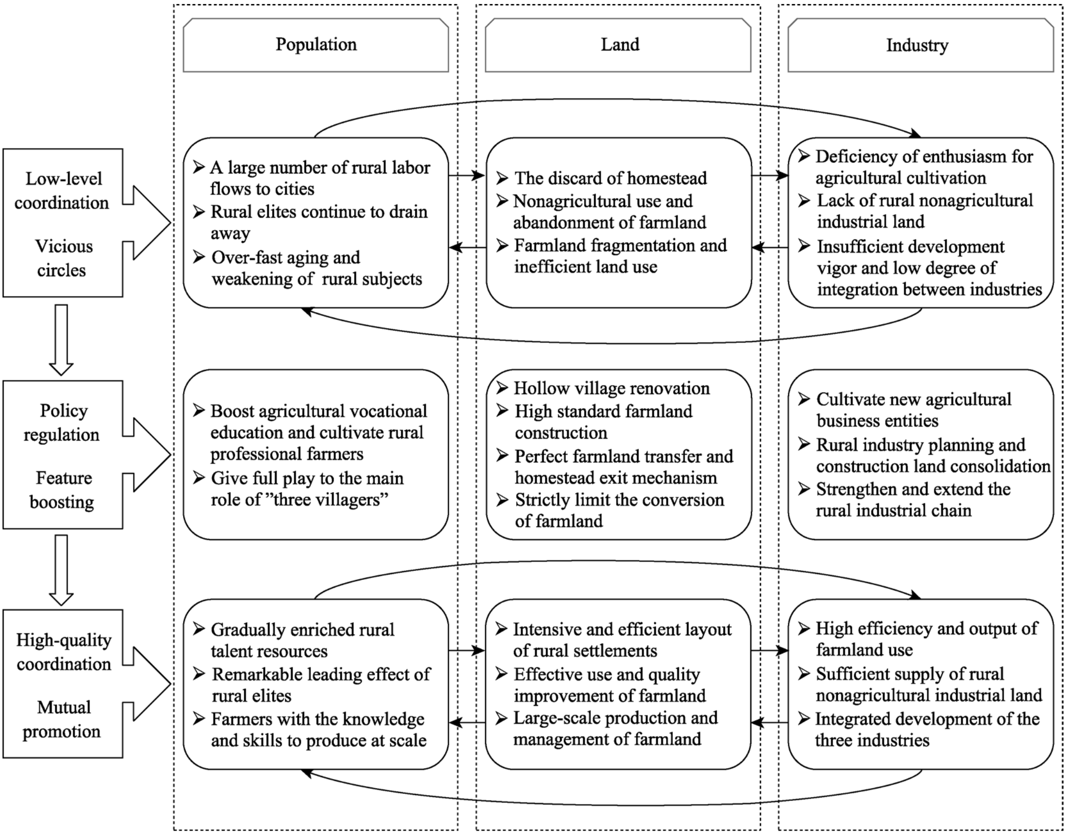

Figure 6 Mechanism of policy regulation for the coupling coordinated development of rural population-land-industry

4.2.2 The influencing factors

The rural PLI coupling coordinated development within the rural territorial system is affected by the comprehensive influence of the rural kernel system and the rural peripheral system. Scientific regulation of the push force of the kernel system and the pull force of the peripheral system can optimize the direction, process, and quality of rural PLI. In the rural kernel system, the rural ontology system represented by the elements of resources and environment has the most important decisive force, which is fundamentally decisive and cannot be effectively regulated by policy. The rural subject system including economic development and agricultural modernization can significantly affect the rural PLI coupling coordinated development. Under the new norm of economic development from quantity-oriented to quality-oriented, rural areas must rely on the advantages of resources, manpower, ecology, and characteristic products to facilitate high-quality economic development. First, according to their resource endowments, rural areas need to explore their comparative advantages, vigorously develop characteristic industries, support the growth of distinctive enterprises, and create a development pattern of "one village, one product" as well as "one county, one industry" (Chen *et al*., 2019). Second, rural areas should be based on an agricultural production basis, promote the integrated development of rural industries, actively construct a modern agricultural production and management system, build an entire agricultural industrial chain, and continuously increase the added value of the agricultural industry. In addition, breaking the urban-rural dual structure and eliminating the institutional constraints that hinder the equal and free flow of urban-rural elements to promote urban talent, capital, management, etc., to go down the countryside to support rural development. Agricultural machinery is an important material basis for modern agriculture. Agricultural machinery use can effectively replace labor input, accelerate the specialized division of labor, improve production efficiency, and promote sustainable agricultural development (Liao *et al*., 2022). In terms of lifting the mechanization and modernization level of agricultural production, although the Chinese government has introduced a series of policies such as subsidies for purchasing machines, there are still problems including unfair financial subsidies, lack of stability and continuity in subsidy programs, and imperfect after-sales service systems in some places (Wang *et al*., 2015b). Therefore, local governments at all levels need to formulate practical subsidy measures to ensure the efficiency and transparency of subsidy funds. In addition, the continuity of the agricultural machinery subsidy program should be ensured as much as possible to enhance the policy effect. Finally, professional and technical personnel should be arranged to strengthen the equipment use training for purchasing farmers and improve the after-sales guarantee service system.

In the peripheral system of rural development, urbanization significantly affects the rural PLI coupling coordinated development, and the q value is 0.0537. In China's rapid urbanization process, a large part of the rural population has outflowed, a large amount of high-quality cultivated land in urban suburbs has been lost, rural industries have declined, and the rural territorial system is undergoing rapid changes. It is undeniable that since the beginning of the 21st century, urbanization has led to rural manpower, land, and capital gathering in cities (Li *et al*., 2018). Instead of playing a role in promoting rural development, cities have hampered rural development and led to "urban prosperity and rural recession" and "rural disease", aggravating rural decline. Against this background, since 2012, the Chinese government has successively implemented important national strategies including the Targeted Poverty Alleviation Strategy, the New Urbanization Development Plan, and the Rural Revitalization Strategy (Liu *et al*., 2020; Liu, 2021). Rural areas should seize the opportunity to boost urban-rural integrated development and accelerate rural modernization.

4.3 Comparison with former research, limitations, and future work

This study constructed a more comprehensive index system including population quality and recessive morphological characteristics of land use, which have been less considered in previous studies. We then assessed the PLI coupling coordinated degree, regional divergence characteristics and driving mechanism in rural China. China's rural development is affected by a combination of multiple factors, where natural resource endowments are always the most important determinants as found in previous studies (Liu and Li, 2017a; Zhou *et al*., 2019). Complex geographical conditions and fragile ecological environments can lead to rural isolation through the “island effect”, and this in turn leads to the uncoordinated development of rural PLI and exacerbates rural poverty (Liu *et al*., 2016; Zhou *et al*., 2020b). Rural socioeconomic factors are the most active factors in rural development, but their influence is lower than that of natural environmental conditions, especially in a country with such a diverse landscape as China (Liu and Li, 2017a; Liu *et al*., 2018; Li *et al*., 2020; Wang *et al*., 2020b; Li *et al*., 2022). In contrast, this study found that nonlinear interaction enhancement often existed when different factors were combined, suggesting that integrated and systematic measures are needed to promote rural development. Therefore, this study proposed targeted policy recommendations in terms of improving the rural PLI development level and regulating the influencing factors.

However, rural PLI coupling coordinated development is a complex systemic process influenced by both the rural kernel system and rural peripheral system. This study revealed the driving mechanisms of the influencing factors, but there are still some factors that have not been considered, such as sociocultural conditions and the policy environment. In addition, although macroscale analysis is essential to identify the main controlling factors of rural development, village-scale research is also indispensable. Future research should, on the one hand, explore modeling methods to quantify sociocultural and policy factors to support a more comprehensive analysis, and on the other hand, conduct microscopic research and analysis on typical villages in different regions to further improve the feasibility of guiding rural development.

5 Conclusions

By measuring the development level of PLI and analyzing the rural PLI coupling coordinated development level in China in 2020, it is found that the development level of the population element was the highest, while the industrial element was the lowest. The rural PLI reached a high-level coupling stage, but the PLI coupling coordinated level was in the stage of approximate incoordination. At the regional level, the rural PLI coupling coordinated degree was the highest in the northeast region, followed by the eastern and central regions, and the lowest in the western region. At the provincial level, Jiangsu had the highest level of rural PLI coupling coordinated degree, while Tibet had the lowest.

Moreover, the intragroup difference was the main source of the overall difference with a contribution rate of more than 80%. The explanatory power of relief (*X*3), elevation (*X*2), agricultural resources and environmental factors (*X*1), agricultural modernization level (*X*5), urbanization level (*X*6), and economic development level (*X*4) gradually decreased. In addition, we found that rural PLI coupling coordinated development was influenced by the combined effects of rural kernel and peripheral systems. The rural kernel system mostly determined the differentiation of rural PLI coupling coordinated development, which was 5.44 times greater than that of the rural peripheral system.

Furthermore, targeted suggestions were put forward to further facilitate rural PLI coupling coordinated development. On the one hand, the development level of PLI should be improved and positive mutual feedback between PLI should be promoted through population quality improvement projects, land consolidation projects and industrial integration development strategies. On the other hand, it is important to scientifically regulate the rural subject system and rural peripheral system to promote the high-quality coordinated development of rural PLI by implementing a "one village, one product" strategy, breaking the urban-rural dual system, improving agricultural machinery subsidies policy, and promoting urban-rural integrated development.

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