



OPEN Spatiotemporal coupling and regional differences analysis between agricultural land use efficiency and rural revitalization in the Yellow River Basin

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The swift advancement of urbanization poses considerable obstacles to the sustainable growth of agriculture and the development of rural regions. The Yellow River Basin, a key area for agricultural production and ecological conservation in China, faces critical challenges such as land resource depletion and uneven rural development. A thorough exploration of the interaction and alignment between agricultural land use efficiency and rural revitalization in the Yellow River Basin is important for advancing sustainable agricultural and rural development. Accordingly, this study utilizes panel data from 62 cities in the Yellow River Basin covering 2013 to 2022. Building on a clear understanding of the coupling mechanism between agricultural land use efficiency and rural revitalization, the research employs a comprehensive approach, integrating Malmquist index analysis, the entropy weight-TOPSIS method, a coupling coordination degree model, the Dagum Gini coefficient, and GIS-based spatial analysis to examine the spatial-temporal evolution and regional disparities in their coupling coordination. The study revealed the following findings: (1) The coupling coordination level between agricultural land use efficiency and rural revitalization in the Yellow River Basin has remained at a “grudging coordination” stage and exhibits an unstable development trend. The fluctuating characteristics of Moran’s I value and the misalignment between the policy framework and its objectives are potential causes of this phenomenon. (2) The cities in the Yellow River Basin are spatially interdependent. The core city radiates resources and economic vitality, driving the development of neighboring cities at the coupling coordination level, while the resource siphon effect remains relatively small. (3) Interregional differences between the upper and middle reaches are the primary sources of variation in the coupling coordination level within the basin. The upstream region has significantly contributed to the reduction in the overall Gini coefficient, leveraging its “late-mover advantage.” In this regard, we put forward suggestions such as transforming the primitive development mode, adhering to the concept of integrated basin development, and emphasizing regionally differentiated policies to provide inspiration for achieving coupling coordination between the two.

Keywords Rural revitalization, Agricultural land use efficiency, Coupling coordination, Spatial-temporal evolution, Yellow river basin

Rural revitalization serves as a vital strategy for China to speed up the modernization of its agriculture and rural areas¹. It is essential for addressing the disparity between urban and rural development in developing nations. Since introducing the rural revitalization strategy at the 19th National Congress of the Communist Party of China, policies that promote rural development, construction, and governance have received considerable attention. In 2022, the Implementation Plan for Rural Construction Actions was launched, providing a

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comprehensive framework for rural development initiatives. In 2023, the Opinions of the Central Committee of the Communist Party of China and the State Council on Strengthening Key Efforts for Promoting Rural Revitalization highlighted the continued strategic significance of rural revitalization in addressing the “three rural issues” (agriculture, rural areas, and farmers) and furthering the modernization of agriculture and rural regions. Agricultural land resources are the cornerstone of agricultural production, directly influencing agricultural efficiency and rural economic prosperity². The Notice on Further Regulating and Accelerating the Comprehensive Land Remediation Pilot, issued by the Natural Resources Department in 2023, emphasizes the strategic importance of agricultural land utilization. Projects such as agricultural land consolidation are identified as systematic supports for implementing the rural revitalization strategy. Obviously, effectively revitalizing and intensively utilizing agricultural land resources is fundamental to the harmonious development of agricultural production, rural livelihoods, and the ecological environment, but it is also crucial for promoting sustainable rural industrial development and fostering a virtuous cycle³. The Yellow River Basin is leading in environmental protection and promoting high-quality agricultural and rural development in China. However, compared to the Yangtze River Basin, Pearl River Basin, and other regions pursuing similar strategies, the Yellow River Basin faces significant gaps in resource and environmental carrying capacity and rural development levels. Accelerated urbanization in the basin has exacerbated challenges such as population decline, severe depletion of agricultural land resources, and disorganized land use. These issues have resulted in prominent agricultural land use problems, including a severe shortage of agricultural land and inefficient utilization, which impede the further implementation of the rural revitalization strategy^{4–6}. Therefore, in the long term, to address the challenges to agricultural and rural development posed by accelerated urbanization, this study selects the Yellow River Basin—a region notable for its natural, economic, and policy characteristics—as the research focus. The goal is to investigate the coupling and coordination relationship, as well as the regional variations, in the spatiotemporal development of agricultural land use efficiency and rural revitalization. This research offers valuable insights for achieving sustainable agricultural and rural development and provides a theoretical foundation and research framework for studying river basins characterized by the development paradigm of “backward-rise-developed.”

Achieving sustainable development in agriculture and rural areas depends heavily on the effective and rational management of agricultural land resources^{7–9}. Previous studies have examined this issue from various perspectives, including the economic¹⁰, social, and ecological¹¹ values of efficient land use. Many believe that the efficient utilization of agricultural land focuses on boosting agricultural productivity through better land use structures, which contributes to the sustainable development of rural areas¹². Scholars focusing on agricultural land use efficiency have primarily explored its driving mechanisms¹³, influencing factors⁶, spatial-temporal evolution¹⁴, and optimal regulation paths¹⁵. Many have developed multi-dimensional index systems for assessing agricultural land use efficiency^{14,16} and have applied total factor productivity methods, such as the stochastic frontier methods¹⁷ and data envelopment analysis⁶, for measurement. Compared to the stochastic frontier method, data envelopment analysis eliminates subjectivity and errors arising from functional specification, making its results more reliable and scientifically valid. As a result, it has become the dominant measurement method^{16–18}. Additionally, studies on factors such as land circulation⁹ and agricultural industrial agglomeration¹⁹ have highlighted the connection between various system elements and agricultural land use efficiency. However, these studies have predominantly focused on national²⁰, provincial²¹, or urban agglomeration levels²², often neglecting the river basin level.

Promoting the rural revitalization strategy plays a crucial role in improving living conditions in rural areas, attracting more capital to the countryside, and fostering a virtuous cycle of rural development^{23,24}. Currently, the development of qualitative research on rural revitalization is closely tied to the evolution of its theoretical foundations and the deepening exploration of implementation paths. Rural revitalization, in theory, is primarily based on the general goals for rural development outlined in the “20-character” framework from the report of the 19th National Congress of the Communist Party of China, which emphasizes “industrial prosperity, ecological livability, rural civilization, effective governance, and affluent life”^{25–27}. Research has progressively expanded on these “twenty characters,” incorporating diverse interpretations and linking them with other factors to develop new insights. As an illustration, rural revitalization is defined as a process that begins with new-type urbanization, advancing through the harmonious development of urban and rural areas to achieve the socialist modernization goal of urban-rural integration^{24,28,29}. The exploration of the path of rural revitalization starts from the basis of the theoretical definition. Related studies address domains such as industrial production^{30,31}, ecological environment³², civilization construction³³, digital economy³⁴, and financial development³⁵, analyzing the internal mechanisms that promote rural revitalization. Building an evaluation system is key to enabling the quantitative analysis of rural revitalization. Related studies have developed an evaluation system for rural revitalization from various aspects of rural construction, including “material civilization and spiritual civilization,” and have used these fields as benchmarks to explore quantitative indicators such as talent, land, and capital³⁶. Furthermore, scholars have employed methods such as the entropy weight method³⁷ and principal component analysis³⁸ to assess rural revitalization levels quantitatively. When it comes to the interrelationship between the two, such as the impact of digital inclusive finance, rural tourism, new-type urbanization, and other factors on rural revitalization or coordinated development, these are mainly assessed using models such as the double fixed effect model³⁹ and the coupling coordination model⁴⁰.

Currently, most research on agricultural land use efficiency and rural revitalization focuses on individual aspects, with limited studies addressing the relationship between the two. The primary focus has been the connection between agricultural land use transformation⁴¹ and agricultural land use remediation^{42,43} and rural revitalization. Agricultural land use transformation research underscores the importance of aligning the development of “population, land, and industry,” providing guidance for rural revitalization by identifying issues related to land use transformation⁴⁴. In contrast, agricultural land use remediation aims to achieve a rational allocation of resources by examining remediation strategies, using differentiated approaches to revitalize

agricultural land resources and alleviate land-use conflicts⁴⁵. The findings of these studies suggest that rational and effective agricultural land use contributes to the overall growth of rural economies, social structures, and cultural aspects. Improving the efficiency of agricultural land use, as a key method of land optimization, not only increases agricultural production but also plays a critical role in refining the rural industrial structure, serving as a major pathway for rural revitalization^{6,46}.

Existing literature primarily focuses on the connotation, evaluation systems, and measurement methods related to agricultural land and rural revitalization, with limited discussion on the internal coupling and associative mechanisms between the two. In particular, there is a noticeable gap in studies addressing the Yellow River Basin—a key region for promoting rural revitalization—and even fewer studies use cities within the basin as the primary research unit. This study utilizes data from 82 prefecture-level cities in the Yellow River Basin to fill these gaps. Based on the coupling coordination mechanism between agricultural land use efficiency and rural revitalization, the study measures their coupling coordination levels and explores their spatial-temporal evolution and regional differences. This research primarily addresses the following objectives: First, it integrates agricultural land use efficiency and rural revitalization into a unified research framework, deconstructs the concepts of both, and analyzes their coupling coordination mechanism. This method aims to fill the gap in existing literature, where studies frequently focus on separate evaluations of individual domains. Second, the study systematically investigates the spatial-temporal evolution characteristics of the coupling coordination level between agricultural land use efficiency and rural revitalization in the Yellow River Basin, with a micro-scale focus on cities in the basin. It dynamically examines the spatial patterns, evolutionary dynamics, and agglomeration types of the coupling and coordinated development between the two, providing insights into their development stages and identifying potential obstacles. Finally, the study explores regional differences in the level of coupling coordination between the two, offering theoretical guidance for achieving balanced regional development. This research provides valuable quantitative and empirical analysis to support the coupling and coordination of agricultural land use efficiency and rural revitalization in the Yellow River Basin and offers theoretical insights for the agricultural and rural development of other river basins.

Theoretical model

Deconstruction of the agricultural land use efficiency system

The prosperity and well-being of rural areas are widely recognized as a multidimensional complex that emphasizes economic growth while also requiring careful consideration of the dynamic balance between residents' well-being, social cohesion, and ecological sustainability^{47,48}. As a complex system, rural areas comprise multiple subsystems, including nature, ecology, society, and the economy. Among these, population, land, and industry (referred to as “population-land-industry”) represent key components of the rural social system, natural resource system, and economic system, encompassing nearly all core elements of rural sustainable development^{49,50}. Specifically, population changes profoundly impact food security and the rural poverty structure. Effective population management and policy regulation are crucial for achieving sustainable rural development. Land, as the spatial foundation for rural populations and industrial activities, provides essential support for other development factors. Industry serves as the central driving force for rural development, facilitating the transition from a predominantly agricultural economy to diversified economic growth. When the coordinated development of “population-land-industry” is not achieved, it can result in a series of interconnected issues, such as labor shortages, reduced land use efficiency, an overly concentrated industrial structure, stagnating economic development, inadequate social services, weakened governance capabilities, cultural decline, and increasing ecological and environmental pressures, all of which hinder the sustainable development of agriculture and rural areas.

The multifunctional value of agricultural land, encompassing food production, ecological services, and economic value, forms the foundation for addressing the diverse needs of rural residents⁵¹. Enhancing agricultural land use efficiency is essentially a process of maximizing output from limited land resources. This process focuses on crop cultivation and output and involves the comprehensive integration of agricultural technology innovation, resource recycling, and ecological environmental protection⁵². By optimizing agricultural land use, resources are allocated efficiently, the full potential of agricultural land is realized, and the integrated development of “population, land, and industry” is promoted. Specifically, at the population level, improving agricultural land use efficiency can increase output per unit of land, directly boosting farmers' economic returns and providing more resources to elevate the living standards of rural residents. At the land level, improving efficiency facilitates the rational allocation and diversification of land resources, enhancing land's overall value and establishing a firm foundation for the sustainable development and use of resources. At the industrial level, enhanced efficiency stimulates the scaling and intensification of agriculture, facilitating the optimization and advancement of the industrial structure⁵³. Based on this, this study defines agricultural land use efficiency as a driving system that mobilizes the diverse functions of rural land and fosters the coordinated development of “population-land-industry.”

Deconstruction of the rural revitalization system

China's agricultural and rural modernization aims to achieve two key long-term goals: one is to ensure national food security and a stable food supply for the population, and the other is to promote the sustained growth of agricultural workers' incomes⁵⁴. However, the rapid progress of urbanization and the increasing emphasis on ecological security have rendered the traditional agricultural development model—relying on long-term inputs of resources such as land and labor, as well as polluting chemicals like industrial fertilizers—unsustainable. Agriculture must transition to a low-negative-externality development model, meaning that production growth and rural development should not harm the ecological environment (excluding minor pollution from reasonable agricultural inputs such as fertilizers and water)^{55,56}. Therefore, agricultural and rural development must follow

a multidimensional, balanced, and sustainable path to achieve a harmonious integration of economic, social, and environmental benefits. Specifically, sustainable rural development requires structural optimization across various domains, including agricultural production, social solidarity and stability, cultural inheritance and promotion, and ecological sustainability⁵⁷. This aligns closely with the strategic goal of rural revitalization: industrial prosperity, ecological livability, rural civilization, effective governance, and affluent life.

When the countryside achieves the coordinated development of the “population-land-industry” system, an optimized land use model and industrial layout can significantly enhance agricultural productivity, stimulate substantial growth in the rural economy, effectively reduce poverty, and realize the overarching goal of rural revitalization—industrial prosperity and affluent life. The creation of more employment opportunities helps solidify social stability and unity in rural areas, aligning with the goal of effective governance. Furthermore, sustainable land management strategies and environmental protection measures maintain ecological balance, preserve rural areas’ natural landscape and cultural heritage, and fulfill the development requirements for ecological livability and rural civilization. Therefore, the coordinated development of “population-land-industry” is essential for fostering sustainable rural construction and a core strategy for achieving the objectives of the rural revitalization overall policy. Consistent with this, and in alignment with the overarching goals of the rural revitalization overall policy, a goal system consisting of five dimensions has been defined: industrial prosperity, ecological livability, rural civilization, effective governance, and affluent life.

Analysis of coupling coordination mechanisms

Coupling coordination refers to the interconnection of two or more systems, wherein they mutually influence and coordinate based on associated logic or through various intrinsic developmental processes, resulting in the emergence of integrated phenomena⁵⁸. This concept is currently widely utilized across multiple fields. The rural revitalization target system and the agricultural land use efficiency driving system mutually influence. There is an interactive coupling and coordination mechanism between the agricultural land use efficiency driving system and the rural revitalization target system, with the coordinated development of “population-land-industry” serving as an intermediary, as illustrated in Fig. 1. As the core spatial foundation for rural economic and social development, improving agricultural land efficiency can optimize population structure, promote efficient land use, and foster industrial agglomeration. In turn, this can stimulate positive interactions between urban capital and agricultural land resources, thus achieving the coordinated development of “population-land-industry.” This coordinated development is a key driver of high-quality rural growth and a central strategy for achieving the objectives of the rural revitalization initiative. Within the framework of socialism with Chinese characteristics, rural revitalization is not only reflected in material support but also the revitalization of dynamic industries and effective governance systems. Its concept provides direction and strategic support for enhancing agricultural land use efficiency⁵⁹. By focusing on improving agricultural land use efficiency and activating key rural development elements, the organic integration of diverse rural businesses can be achieved, effectively advancing the execution of the rural revitalization strategy. Thus, nurturing new forces for rural development and persistently promoting the rural revitalization strategy through establishing a coupling coordination

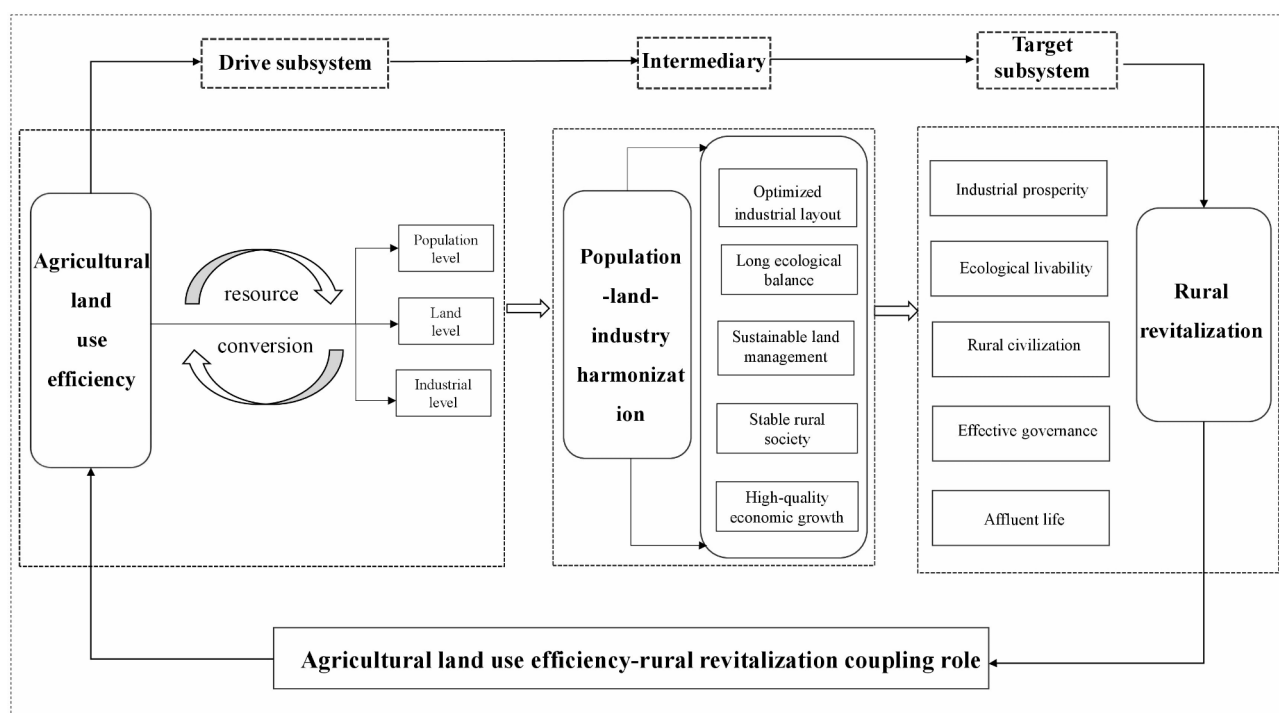


Fig. 1. The coupling coordination relationship between agricultural land use efficiency and rural revitalization.

mechanism is of utmost importance. This mechanism, with agricultural land use efficiency as the driving force, rural revitalization as the target, and coordinated development of “people-land-industry” as the intermediary, will help foster sustainable progress. Additionally, the developmental trends influence the coupling relationship between rural revitalization and agricultural land use efficiency. As the impact of rural revitalization increases, so does the efficiency of agricultural land use. A stronger coupling and coordination between the two will facilitate the ongoing promotion of the rural revitalization strategy.

Materials and methods

Method overview

This study focuses on three main aspects (see Fig. 2): First, agricultural land use efficiency and rural revitalization are integrated into a unified research framework. Both concepts are deconstructed, and the coupling coordination mechanism between them is analyzed. Based on this, a multi-dimensional index system is constructed for each, and the development level and coupling coordination degree of both are measured using methods such as the Malmquist total factor productivity index analysis (see Appendix 1.1), the entropy weight-TOPSIS method (see Appendix 1.2), and the coupling coordination degree model (see Appendix 1.3). This approach aids in thoroughly understanding the present condition and obstacles of rural development, providing a solid theoretical framework for achieving effective synergy between the two. Second, with regard to time-series characteristics, the Moran Index (see Appendix 1.4) and the standard deviation ellipse method (see Appendix 1.5) are used to

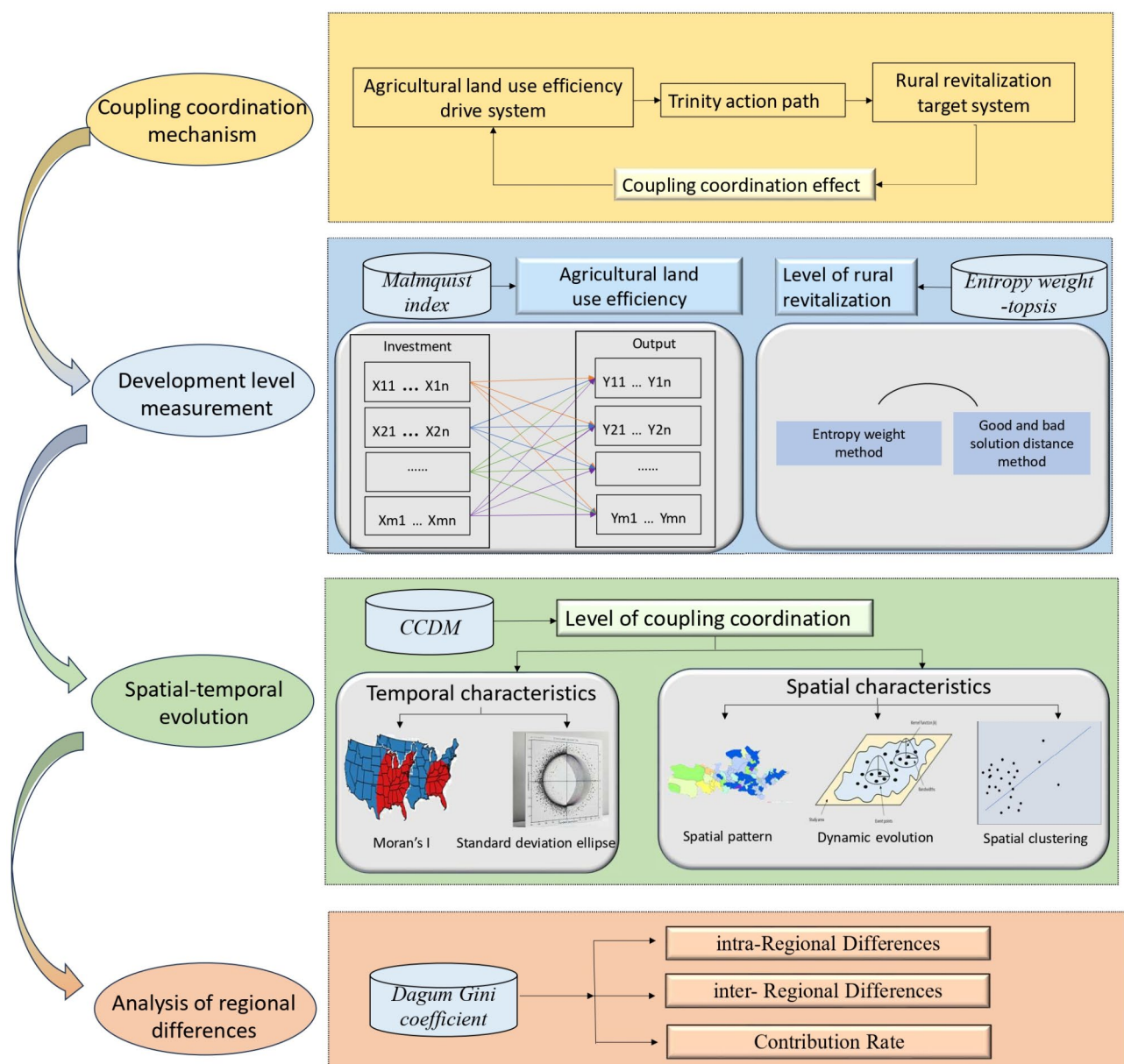


Fig. 2. Research framework.

analyze the overall development trend of the coupling and coordinated development of agricultural land use efficiency and rural revitalization in the Yellow River Basin. This is crucial for observing the dynamic spatial relationship of the coupling coordination level over time and identifying the dominant direction and trends in spatial distribution. In terms of spatial characteristics, kernel density estimation (see Appendix 1.6) and hotspot analysis (Getis-Ord G^*i) (see Appendix 1.7) were used to analyze the dynamic evolution and local agglomeration characteristics of the coupling coordination between agricultural land use efficiency and rural revitalization. This is crucial for understanding their interrelationship across different spatial scales and stages of development. Third, the study emphasizes the development heterogeneity of the upper, middle, and lower reaches of the Yellow River. Considering regional differences, the Dagum Gini coefficient (see Appendix 1.8) is utilized to explore the variations in the coupling coordination of agricultural land use efficiency and rural revitalization along the upper, middle, and lower reaches of the Yellow River. This is significant for achieving differentiated regulation of the river basin and deepening research on its development.

Study area

The Yellow River basin is China's significant agricultural production and ecological security region. Starting in the Tibetan Plateau to the west, it passes through nine provinces, such as Gansu, Shaanxi, and Shandong, forming a distinct shape. Its total length spans 5,464 km. In line with the Outline of the Yangtze River Economic Belt Development Plan, Sichuan Province falls within the Yangtze River Economic Belt. Hulunbeier, Xing'anmeng, Tongliao, and Chifeng in the Inner Mongolia Autonomous Region are part of the Northeast Region. Considering the natural resources, socioeconomic conditions of agricultural production, and data availability, 82 prefecture-level administrative districts across eight provinces in the Yellow River Basin were ultimately selected for the study. Following the definition provided by the Yellow River Conservancy Commission of the Ministry of Water Resources, the Yellow River Basin has been segmented into three research areas: the upper, middle, and lower reaches (see Fig. 3). The upper reaches of the Yellow River Basin, consisting of Qinghai, Gansu, and Ningxia Provinces, include 26 prefecture-level cities. These areas exhibit sizeable agricultural land per unit but suffer from lower land quality, fragile ecosystems, and constrained socioeconomic conditions, hindering agricultural and rural development. The middle reaches of the Yellow River comprise 26 prefecture-level cities across four provinces: Gansu, Shanxi, Shaanxi, and Henan. The climate in this region is humid and conducive to farming; however, soil erosion is a significant issue, requiring special attention to the various risks of agricultural land. Encompassing 30 prefecture-level cities, the lower reaches of the Yellow River stretch across two provinces: Shandong and Henan. These regions possess ample light and heat resources, abundant rainfall, and favorable socioeconomic development conditions, making them significant grain-producing areas in China.

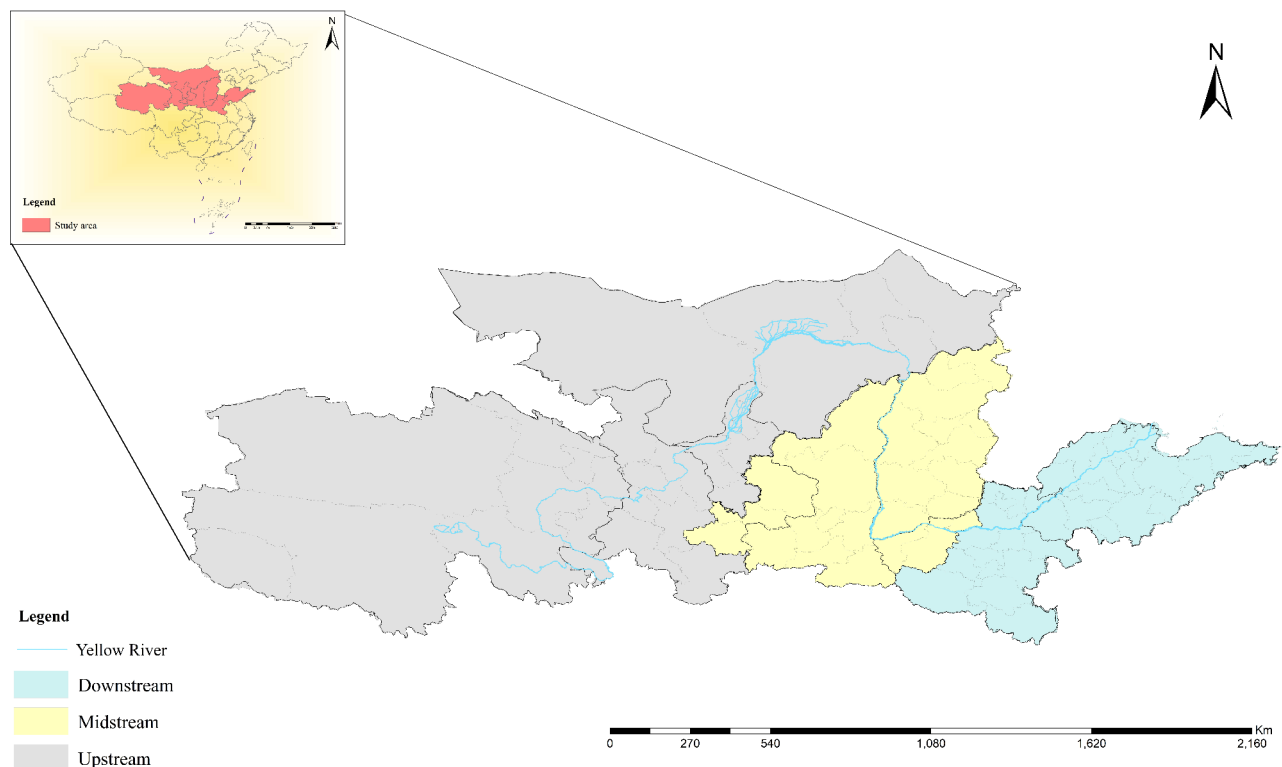


Fig. 3. The geographical scope of this study.

Construction of the evaluation index system

Rural development requires the use of various resource elements, such as land, labor, and capital. The key to enhancing agricultural land use efficiency is minimizing resource inputs while maximizing economic output⁶⁰. Thus, based on the systematic dimensioning and mechanism analysis of agricultural land use efficiency outlined above, an input-output efficiency index evaluation system is established. The input dimension specifically addresses the resources associated with farmland, including the utilization of agricultural resources such as land and labor. This dimension is measured using indicators like the cropland area per laborer. The output dimension focuses on the economic output and social effects of agricultural land use activities, which are assessed using indicators such as the average production value of agriculture, forestry, livestock, and fisheries. Specific indicators and calculation formulas are provided in Appendix 2.

The General Requirements for Rural Revitalization provide significant guidelines for addressing the “Three Rural Issues” and are reasonable for assessing the progress of rural revitalization. However, scholars hold varying opinions on the indicator layers defined by the five dimensions. In the context of industrial prosperity, Wang et al.⁶¹ emphasized the role of digital technology in empowering rural industrial development, while Xu et al.⁶² attributed industrial prosperity to production technology, species diversity, and other factors. In line with the current national policy directives and based on the previously outlined deconstruction of the dimensions and analysis of the mechanisms underlying the rural revitalization system, it is proposed to establish an indicator evaluation system for rural revitalization. This system should encompass five key dimensions: industrial prosperity, ecological livability, rural civilization, effective governance, and affluent life. The system is designed with the principles of scientific rigor, systematic structure, and practical applicability in mind. The “Guiding Opinions of the State Council on Promoting the Revitalization of Rural Industries” emphasizes that a thriving industrial sector is a crucial foundation for rural revitalization. Industrial prosperity represents the integration of rural resources and the transformation of the economy, achieved through the development of characteristic industries. This dimension is assessed using indicators such as the economic contribution of the rural service industry. Additionally, the “Five-Year Action Plan for the Improvement of Rural Human Settlements (2021–2025)” mandates that by 2025, substantial progress should be made in constructing beautiful and ecologically livable villages. Therefore, ecological livability necessitates the reasonable planning of rural ecological spaces, which forms the foundation for achieving the ecological goal of enhancing the carrying capacity of rural resources⁶³. This dimension is assessed using indicators such as the per capita ecological green area. Rural civilization aims to advance the construction of rural society, offering a conducive environment and spiritual fortitude for implementing rural revitalization strategies and establishing picturesque and harmonious rural areas, as assessed through indicators like the number of civilized villages at the county level and above. Effective governance enhances the modernization of rural governance capacity by promoting grassroots democracy and fostering the trinity governance mechanism, which involves rural self-governance, legal governance, and moral principles. This aligns with the “Guiding Opinions of the CPC Central Committee and the State Council on Strengthening and Improving Rural Governance,” which states the need to enhance the rural governance system by integrating party-led self-governance, the rule of law, and moral governance. This dimension is mainly assessed through indicators such as the number of cases of security management breaches handled. Affluent life underscores the importance of elevating rural livelihood security to enhance people’s well-being, directly reflecting the benefits of industrial prosperity, among other factors. This is evaluated through the per capita disposable income of rural residents. Specific indicators and calculation formulas are provided in Appendix 3.

The data are mainly sourced from the 2013–2022 Yellow River Basin City Statistical Yearbook and the statistical yearbooks and bulletins of 82 cities and municipalities. The analysis uses the city as the basic unit without accounting for heterogeneity at the county or village level, such as potential differences in the degree of coupling coordination between mountainous areas and rural plains within the same city. Linear interpolation is used to fill missing values, though it overlooks the impact of nonlinear factors, such as unexpected policies or natural disasters.

Results and analysis

Measurement of agricultural land use efficiency and rural revitalization level

For a time series evaluation of agricultural land use efficiency and rural revitalization levels, see Appendix 4. In light of the measurement findings, the efficiency of agricultural land use exhibited an unstable development trend during the research period, which generally aligned with the fluctuating level of rural revitalization. For instance, from 2014 to 2016, the efficiency exhibited periods of increase followed by decrease. This trend supports the coupling coordination mechanism described above. The development trajectories of each influence the interaction between rural revitalization and agricultural land use efficiency. When agricultural land use efficiency and rural revitalization progress together during a rapid development phase, improvements in agricultural land use efficiency can accelerate the circulation of rural land management rights and the integration of collectively operated construction land into the market, thereby activating rural land assets, unlocking their value, and fostering the coordinated development of “population-land-industry,” which in turn promotes rural revitalization. However, when one factor develops too quickly—such as when rural revitalization progresses faster than the optimization of agricultural land use efficiency—it may result in a situation where the capital and technology invested by the government cannot be effectively converted into the necessary capital to enhance agricultural land use efficiency, leading to wasted resources and inefficiency. When rural revitalization is low, its implementation yields less significant results, and the improvement in agricultural land use efficiency is similarly constrained. This results in poor coupling and coordination between the two, which impedes the continuous advancement of the rural revitalization strategy.

Interval	Level	Interval	Level
[0, 0.1)	Extreme imbalance	[0.5, 0.6)	Grudging coordination
[0.1, 0.2)	Severe imbalance	[0.6, 0.7)	Primary coordination
[0.2, 0.3)	Moderate imbalance	[0.7, 0.8)	Moderate coordination
[0.3, 0.4)	Mild imbalance	[0.8, 0.9)	Good coordination
[0.4, 0.5)	On the verge of imbalance	[0.9, 1.0]	High-quality coordination

Table 1. Stages of the coupling coordination level.

Year	Descriptive statistics		Spatial autocorrelation coefficient		
	Average value	Standard deviation	Moran's I	Z Value	P Value
2013	0.609	0.156	0.306	4.403	0.000
2016	0.610	0.151	0.270	3.899	0.000
2019	0.611	0.138	0.355	5.064	0.000
2022	0.620	0.147	0.299	4.286	0.000

Table 2. Descriptive statistics and Moran's I values of the coupling coordination level in the yellow river basin, 2013–2022.

Temporal characteristics of the coupling coordination level

To more accurately assess the coupling coordination level and developmental stage of agricultural land use efficiency and rural revitalization, the coupling coordination level is categorized into ten stages based on the research of Bo et al.⁶⁴, as depicted in Table 1.

According to Table 2, overall, the level of coupling coordination between agricultural land use efficiency and rural revitalization in the Yellow River Basin slightly increased from 0.6090 to 0.6202 between 2013 and 2022, reflecting a 1.8% growth and an annual average growth rate of 0.18%. This indicates a slight upward trend in the coupling coordination level between agricultural land use efficiency and rural revitalization during the study period. However, the overall level remains low, with both systems in a long-term “grudging coordination” state characterized by instability. In other words, the development of both may approach a fragile equilibrium. Once impacted by external conditions or issues in one aspect, the entire system may quickly lose balance, hindering the development process. On the one hand, this reflects the challenges in promoting rural revitalization or improving agricultural land use efficiency in most areas of the basin, as supported by the analysis of agricultural land use efficiency and rural revitalization levels in the previous section. On the other hand, this “grudging coordination” state suggests that some coordination exists within the system, but it fails to establish a solid synergistic mechanism due to multiple factors, including policy orientation⁶⁵. In Appendix 5, we explore in detail the possible disconnect between policy orientation and actual implementation, which may be one of the potential causes of the observed destabilizing features. In terms of spatial trends (see Table 2), Moran's I indices for the coupling coordination between agricultural land use efficiency and rural revitalization in 2013, 2016, 2019, and 2022 show consistently significant positive values, indicating strong positive clustering characteristics between the two. However, Moran's I value also exhibited fluctuations in positive correlation, characterized by an “inverted Z-shaped” trend of high-low-high-low. Further correlating the positive spatial correlation with spatial heterogeneity, we find that fluctuations in the spatial aggregation intensity of the coupling coordination levels may lead to synchronous changes in the significance of the differences in coupling coordination levels across regions, resulting in unbalanced and unstable development of coupling coordination in the Yellow River Basin. Specifically, fluctuations in the degree of spatial agglomeration of the coupling coordination level can lead to uneven distribution of resources (such as agricultural land, labor, and technology) among regions and limited agricultural technological progress and knowledge spillovers. This, in turn, restricts further coupling coordination development in certain regions⁶⁶. For example, when the coupling coordination level in a region is highly concentrated, it tends to attract more resources, creating a virtuous cycle that enhances the coupling coordination level. However, fluctuating spatial agglomeration can restrict the adequate inflow of resources and may cause delays in the coupling coordination level of that region. Regarding the changing trend (see Fig. 4), the center of gravity for the coupling coordination between agricultural land efficiency and rural revitalization in the Yellow River Basin has moved in a “northwest-northeast-southeast” direction from 2013 to 2022. The centroid of the ellipse is positioned in the eastern part of the basin, with a more pronounced shift observed in the east-west direction compared to the north-south direction. This indicates that the coupling coordination of agricultural land use efficiency and rural revitalization in the eastern part of the basin is better than that in the western part, and the changes in the coupling coordination in the east-west direction are more significant than those in the north-south axis.

In summary, the coupling coordination level in the Yellow River Basin is in the “grudging coordination” stage, indicating that most areas in the basin lack stability in promoting rural revitalization or enhancing agricultural land use efficiency. While the spatial distribution of coupling coordination levels exhibits some clustering, the persistent and stable east-west horizontal divergence also contributes to the significant gaps in coupling

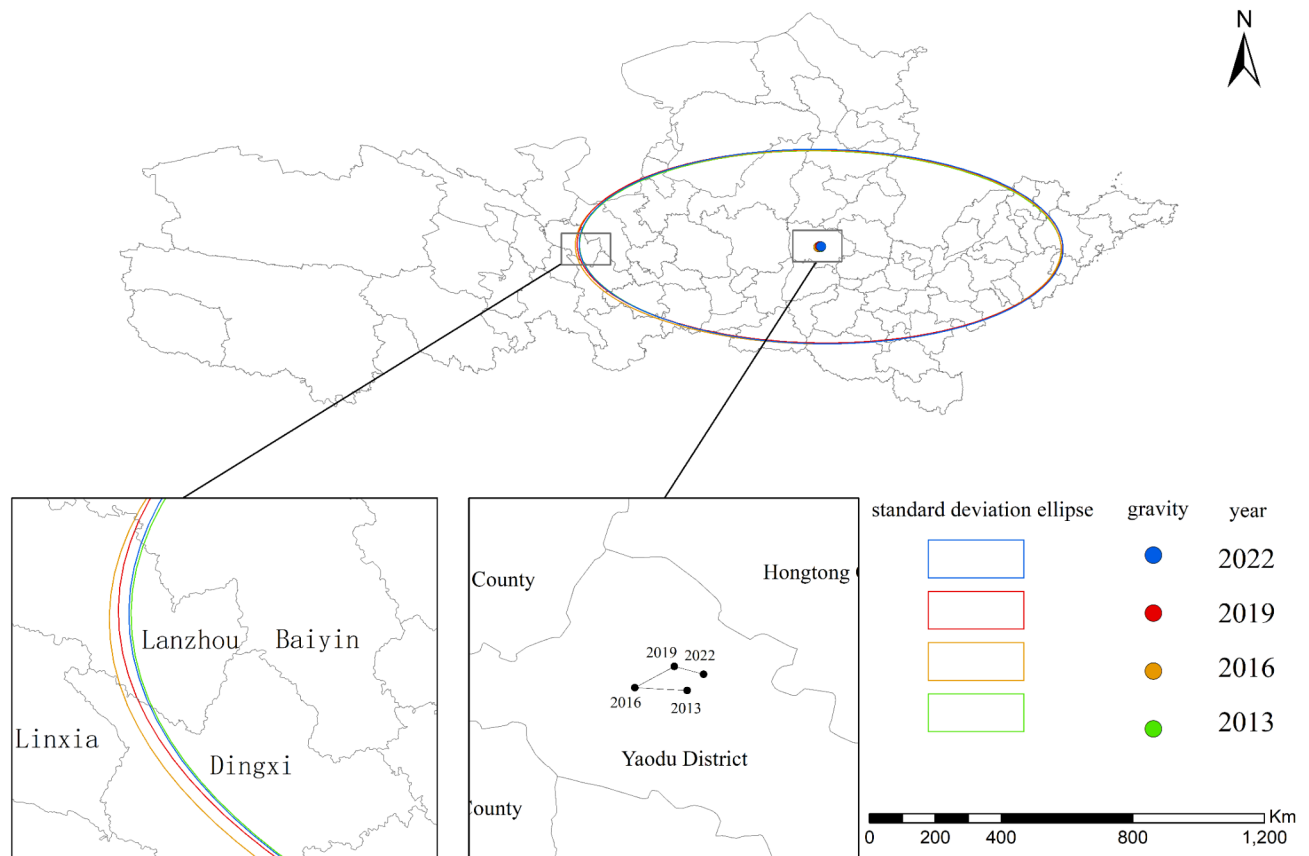


Fig. 4. Variation trend of the coupling coordination level in the Yellow River Basin, 2013–2022.

coordination levels within the watershed. China's development strategy of "developing the eastern region first to support the advancement of the western region," implemented during the initial phase of "reform and opening up," has led to a significant disparity in both the quality and pace of development between the eastern coastal region and the western region. This has profoundly impacted the distribution and evolution of coupling coordination levels within river basins. The modest initial quantitative advantage of the eastern region may amplify significantly over time, resulting in and exacerbating a phenomenon commonly observed in economic and social development known as the "power law distribution" or the "Matthew effect." From the viewpoint of comprehensive growth, establishing a land transfer service platform can effectively facilitate the transfer of idle agricultural land from farmers to specialized cooperatives, thereby improving agricultural land use efficiency and increasing farmers' income levels⁶⁷. From the standpoint of spatial layout planning, future efforts should rely on scientific planning to rationally organize rural industrial development and living spaces. The government can employ incentives, such as financial compensation, to guide remote and scattered traditional settlements toward centralized living areas, gradually narrowing the spatial divide and stabilizing the traditional settlement pattern. This approach will contribute to forming an intensive agricultural production base and a stable rural economic structure, thereby providing strong support for enhancing the coupling coordination between agricultural land use efficiency and rural revitalization.

Spatial characteristics of the coupling coordination level

Spatial pattern characteristics

To explore the spatial transformation of the coupling coordination level between agricultural land use efficiency and rural revitalization, visualization maps were generated using ArcGIS software for 2013, 2016, 2019, and 2022 (see Fig. 5).

From 2013 to 2022, the coupling coordination level between agricultural land use efficiency and rural revitalization in the Yellow River Basin demonstrated a consistent increase. The number of cities experiencing "moderate imbalance" or below has decreased, while the count of cities exhibiting "moderate coordination" has increased. In 2013, the greatest number of cities experiencing an imbalance in the coupling coordination level of agricultural land use efficiency and rural revitalization was observed, primarily concentrated in western Qinghai, western Gansu, northern Ningxia, and northern Shanxi. The number of low-level cities in 2022 is at its lowest, decreasing by approximately 10% compared to the number of cities in 2013. Additionally, the number of cities in the coordination stage increased to two, with Xi'an city exhibiting "good coordination" for agricultural land-use efficiency and rural revitalization throughout the study period. This suggests that with China embarking on the long-term implementation of policies such as the Strategic Plan for Rural Revitalization (2018–2022) and the

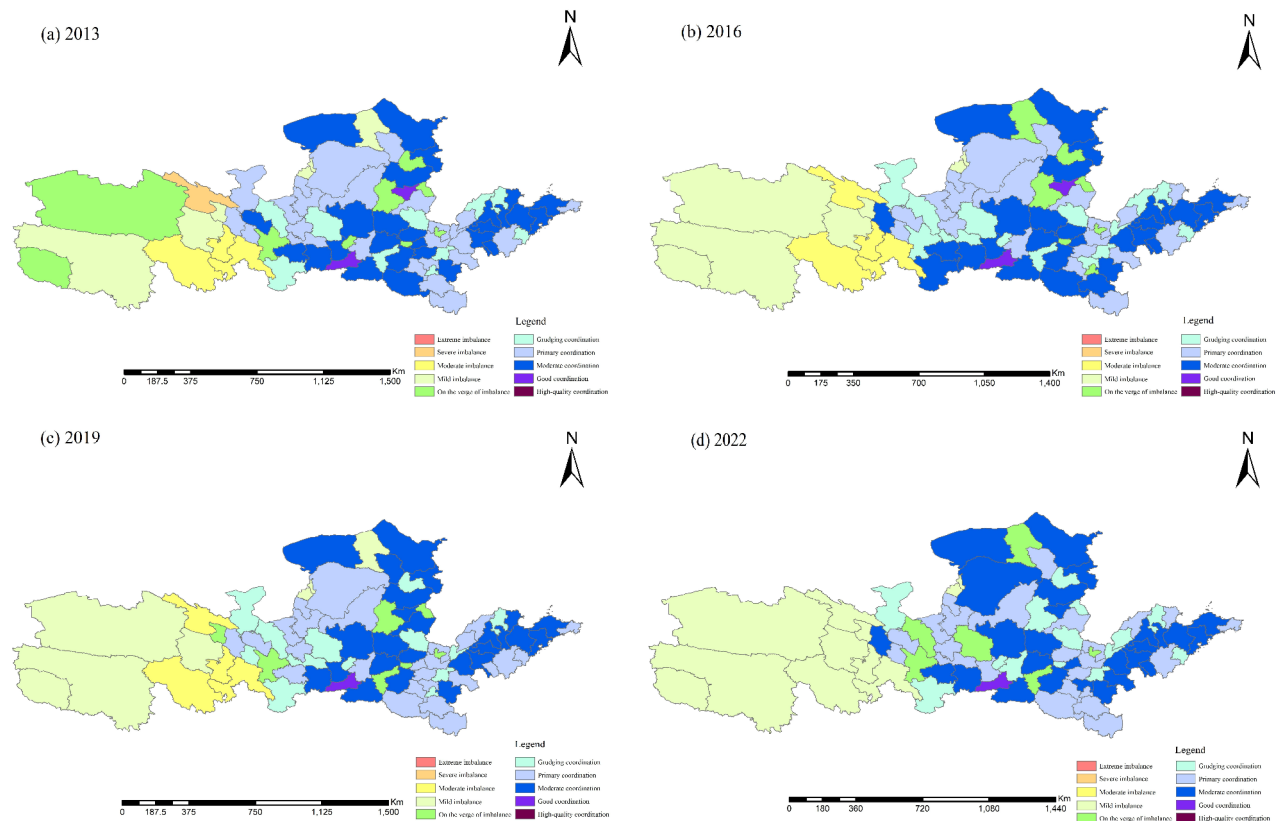


Fig. 5. Spatial pattern of the coupling coordination level in the Yellow River Basin, 2013–2022. (a), (b), (c), and (d) depict the spatial patterns of coupled coordination levels in the study area for the years 2013, 2016, 2019, and 2022, respectively. (The map was drawn using ArcGIS 10.7 software, accessed at <https://www.esri.com/en-us/arcgis/products/arcgis-desktop/resources>).

Ecological Protection and High-Quality Development of the Yellow River Basin, the overall level of coupling and coordination in the basin has increased, leading to a gradual reduction in the number of dysfunctional cities. The ongoing promotion of the rural revitalization strategy can enhance agricultural land use efficiency, optimize industrial layout, and contribute to rural revitalization. Concurrently, Xi'an, a pivotal node in constructing China's "Belt and Road Initiative," is the sole central city in Northwest China. This positioning afforded it significant advantages in resource integration and agricultural planning, consequently establishing its status as a "good coordination" city for an extended period⁶⁸. This implies that while agricultural land use efficiency and rural revitalization are inherently linked to rural areas, the urbanization rate in Chinese cities significantly influences the coordination between these two aspects. The rapid and excessive pace of urbanization has made many villages unsustainable in the long term, and the issue of rural decline, evident in numerous villages experiencing population hollowing, has posed a challenge to the sustainability of urbanization in China. This outcome will impact the interconnected and coordinated relationship between agricultural land use efficiency and rural revitalization, thus the execution of the rural revitalization plan.

The coupling and coordination levels of agricultural land use efficiency and rural revitalization exhibit a "core-periphery" pattern, with lower levels observed upstream, higher levels downstream, and higher levels in the central city and lower levels in peripheral cities. The spatial distribution pattern of the coupling coordination level of agricultural land use efficiency and rural revitalization from 2013 to 2022 remains relatively stable, primarily in cities with "mild imbalance" or below and those with "primary coordination" levels or above. Cities situated at the critical juncture between coordination and imbalance, i.e., "on the verge of imbalance" and "grudging coordination," exhibited significant fluctuations and unstable spatial distributions, as evidenced by the north-central Gansu and north-central Shanxi regions. The majority of "good coordination" cities serve as provincial capitals within the basin, while "primary coordination" and "moderate coordination" cities predominantly cluster around these provincial capitals. Capital cities such as Xi'an, Hohhot, Zhengzhou, and Qingdao have emerged as high-value zones for the level of coupling coordination. Cities that are imbalanced in agricultural land use efficiency and rural revitalization are mainly located in the upper part of the basin. Xining, Haibei Tibetan Autonomous Prefecture, and Gannan Tibetan Autonomous Prefecture have emerged as low-value areas in terms of coupling coordination levels. Cities with "grudging coordination" levels of coupling coordination tend to cluster in regions bordering the Yellow River Basin's upper and middle reaches and the Yellow River Basin's middle and lower reaches.

Dynamic evolution characteristics

By utilizing time series analysis and spatial pattern characterization, our study aimed to investigate the dynamic evolution characteristics of the coupling coordination between agricultural land use efficiency and rural revitalization in the Yellow River Basin (upper reaches) from 2013 to 2022. MATLAB was employed to generate kernel density estimates, as illustrated in Fig. 6. The center of the kernel density distribution for the entire Yellow River basin gradually shifted to the right, with an increasing peak value over the study period. Furthermore, the shape of the peak narrowed from a broad curve, indicating a continuous enhancement in the coupling and coordination level between agricultural land use efficiency and rural revitalization in the Yellow River Basin. During the study period, the distribution primarily manifests as a single peak with a slight leftward bulge. Over time, it may evolve into a bimodal peak trend, exhibiting a slight polarization in the coupling and coordination levels. An analysis of the upstream, midstream, and downstream regions revealed that the evolutionary patterns of the downstream areas and the entire Yellow River basin tended to be consistent, characterized by a predominance of single peaks. However, there was a particular bulge on the left side from 2013 to 2017, which gradually converged to a single-peak pattern, and there were apparent fluctuations in the peak value of the central peak. This indicates that the level of coupling coordination in the downstream area oscillates upward, but the polarization gradually weakens. The center of the kernel density distribution in the midstream region shifted from left to right over the study period, with a persistent single-sided peak. The distance between the central and side peaks increased, and the center of the kernel density distribution was further to the left than in other regions. This suggests that the level of urban coupling coordination in the midstream region initially increased and then decreased, indicating internal differences and a relatively low level of coupling coordination. The kernel density curve in the upstream region exhibited a lower peak value and wider wave width, suggesting an expanding difference in the level of coupling coordination among cities in this region. Overall, the level of coupling coordination in the Yellow River Basin has been increasing. However, attention should be given to the widening differences within the upstream and midstream regions, as these differences may exacerbate the regional imbalance in agricultural and rural development in the Yellow River Basin.

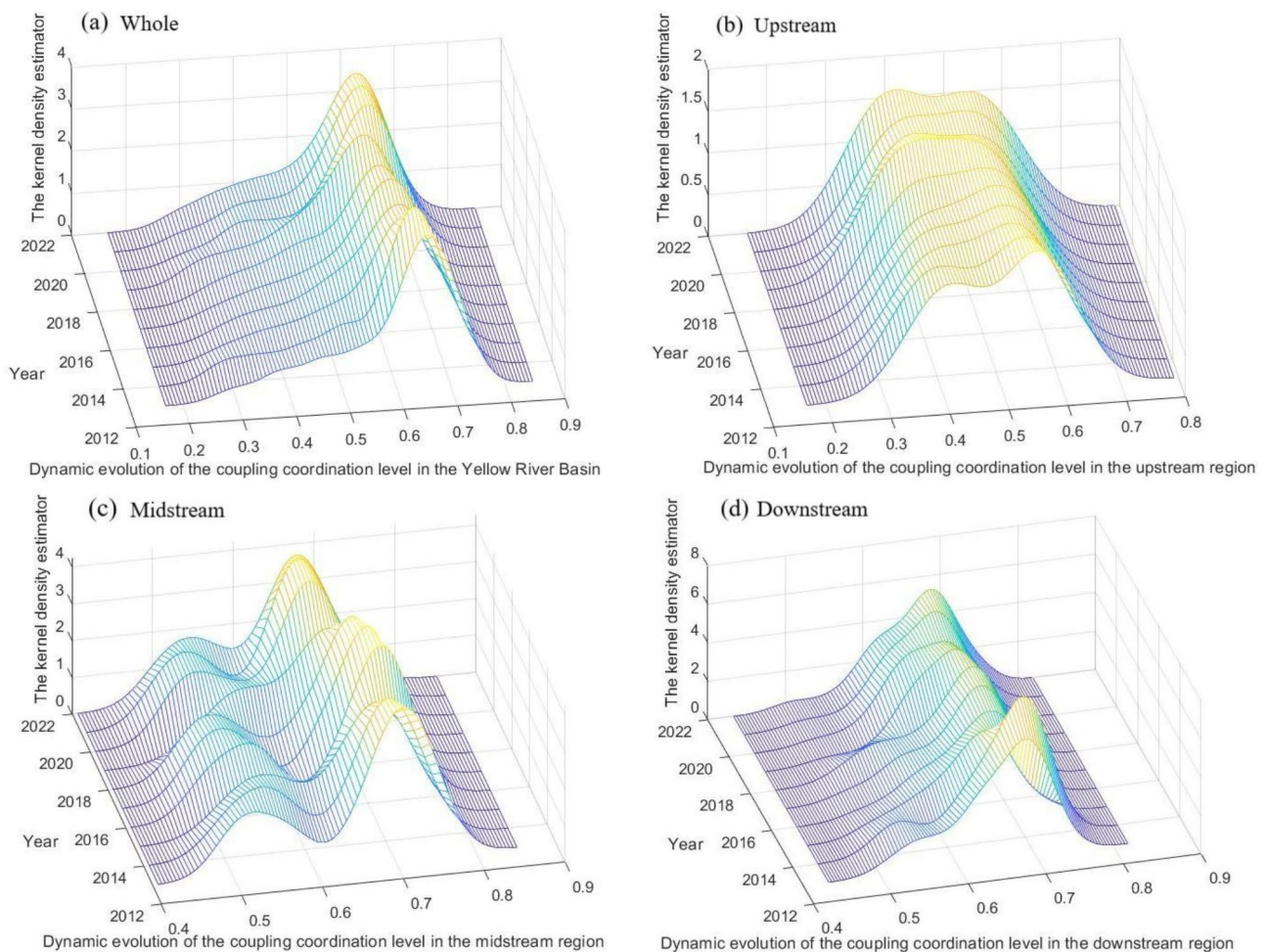


Fig. 6. Dynamic evolution of the coupling coordination level in the Yellow River Basin (upstream, midstream, and downstream), 2013–2022. (a) the Yellow River Basin as a whole; (b) the upstream region of the Yellow River Basin; (c) the midstream region of the Yellow River Basin; (d) the downstream region of the Yellow River Basin.

Spatial clustering characteristics

Spatial correlation exploration is a necessary prerequisite for further characterization of local spatial agglomeration, and the global Moran's I index is an essential method for determining whether there is a spatial correlation between the coupling coordination level of agricultural land use efficiency and rural revitalization. Following testing, the global Moran's I values for the coupling coordination level of agricultural land use efficiency and rural revitalization in the Yellow River Basin during the study period were all significantly positive, with corresponding Z values exceeding 3, indicating a strong positive spatial correlation. The level of coupling coordination is influenced by geographic proximity. To better identify strong and weak influence points for assessing the level of coupling coordination, the local spatial dispersion characteristics of coupling coordination between agricultural land use efficiency and rural revitalization in the Yellow River Basin for 2013, 2016, 2019, and 2022 were examined using the hotspot analysis method (Getis-Ord G^* i). Using the natural breakpoint classification method, the genes were classified into hotspot areas, subcoldspot areas, and coldspot areas. The results are depicted in Fig. 7. Due to space limitations, the detailed analysis of hotspot areas, sub-hotspot areas, coldspot areas, and sub-coldspot areas based on different cities can be found in Appendix 6.

The distribution of hot and cold spots at the coordinated level of agricultural land use efficiency and rural revitalization in the Yellow River Basin from 2013 to 2022 exhibited a spatial pattern of “hot in the east and cold in the west.” Hot and cold spots exhibited diverse spatial distributions across regions, reflecting significant regional disparities. The hotspots are predominantly located in the middle and lower reaches of the basin, illustrating volatile spatial clustering. Notably, the downstream areas with better production and living conditions do not exhibit a significant agglomeration effect compared to the midstream areas. It is widely acknowledged that industries diversify and cluster in larger cities while specializing in smaller cities. This phenomenon is tentatively explained in a broader context as an outcome of the interaction between the urban scale and agglomeration effects⁶⁹. Notably, the larger the city is, the more quickly it attracts the agglomeration of the modern industrial

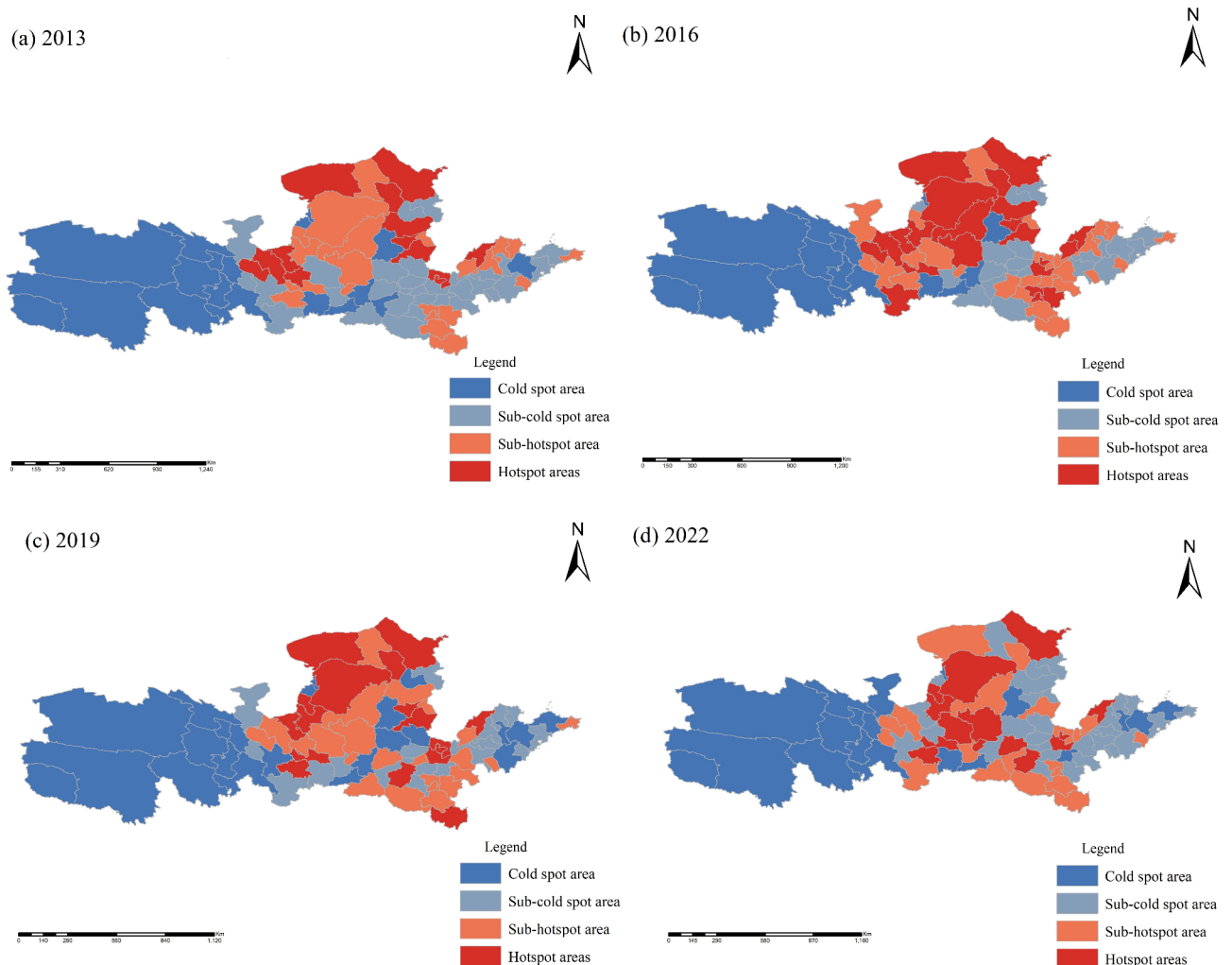


Fig. 7. Spatial clustering of the coupling coordination level in the Yellow River Basin, 2013–2022. (a), (b), (c), and (d) depict the spatial clustering of coupled coordination levels in the study area for the years 2013, 2016, 2019, and 2022, respectively. (The map was drawn using ArcGIS 10.7 software, accessed at <https://www.esri.com/en-us/arcgis/products/arcgis-desktop/resources>).

Year	Overall difference	Intra-regional differences			Inter-regional differences			Contribution rate (%)		
		1	2	3	1-2	1-3	2-3	Gw	Gnb	Gt
2013	0.138	0.214	0.111	0.058	0.176	0.143	0.087	27.598	41.168	31.234
2014	0.136	0.212	0.111	0.053	0.176	0.141	0.085	27.312	41.583	31.105
2015	0.139	0.206	0.113	0.072	0.171	0.146	0.093	28.585	39.049	32.366
2016	0.137	0.203	0.109	0.071	0.168	0.143	0.092	28.739	37.444	33.817
2017	0.134	0.199	0.108	0.072	0.165	0.140	0.092	28.896	37.121	33.983
2018	0.137	0.199	0.109	0.073	0.167	0.143	0.092	28.536	39.106	32.358
2019	0.126	0.183	0.098	0.061	0.155	0.134	0.080	27.526	42.696	29.777
2020	0.132	0.202	0.098	0.065	0.163	0.144	0.082	31.287	40.731	27.982
2021	0.129	0.198	0.098	0.062	0.160	0.139	0.080	28.111	40.539	31.351
2022	0.128	0.196	0.097	0.061	0.164	0.142	0.083	27.869	42.565	29.566

Table 3. Dagum Gini coefficient and decomposition results of the coupling coordination level in the yellow river basin, 2013–2022. Note: Group codes 1, 2, and 3 represent the upper, middle, and lower reaches of the Yellow River Basin, respectively. Gw is the intraregional component, Gnb is the interregional component, Gt is the intensity of the transvariation component, and $G = Gw + Gnb + Gt$.

sector. Meanwhile, the city continuously pushes the traditional industrial sector (e.g., agricultural production) outward as transportation infrastructure and information technology enhancements accelerate the expansion of the traditional industrial sector. The downstream area is a well-developed region in the Yellow River Basin with a high level of modernization; however, agricultural land use and rural revitalization fall under traditional production centered on rural areas, making it challenging to form clusters in the downstream area. The middle reaches of the region abound in grasslands and pastures, making it the most densely populated area in terms of agricultural labor in the Yellow River Basin, with a general identity of agricultural production and rural culture. These factors collectively contribute to the concentration of hot zones in the middle reaches.

Based on spatial characterization, it is found that the spatial influence of high-level cities (referred to as core cities in this paper) on neighboring cities is more pronounced, with their radiation effect being stronger than the siphoning effect. In the context of positive regional spatial correlation, two situations need to be considered: First, when the development level of the core city is significantly higher than that of neighboring cities, it can attract resources from these areas, forming a development “hotspot” and causing the neighboring cities to lag, thus creating a siphon effect. Second, when the core city’s development can drive neighboring cities, the interdependence between their developments increases, leading to a radiation effect⁷⁰. The spatial dispersion characteristics of the coupling coordination level in the Yellow River Basin reveal that hotspot areas are primarily concentrated in the core cities or economically developed regions, indicating that these areas are experiencing the radiation effect. Simultaneously, the spatial pattern reflects the “core-periphery” characteristic, where the polarized status of core cities—due to geographic location, policies, and other factors—may result in a relatively low level of development in neighboring cities, suggesting the presence of negative spillover effects. When the spatial autocorrelation effect becomes more significant (with a higher Moran’s I value), the siphoning effect may be weakened by the overall positive aggregation. However, it is also possible that the siphoning effect still exists, but the positive radial effect becomes more spatially dominant. This conclusion is quantitatively verified in detail using a spatial Markov chain model in Appendix 7.

Analysis of regional differences in the coupling coordination level

To accurately discern the components of regional differences in the coupling coordination level between agricultural land use efficiency and rural revitalization in the Yellow River Basin, intraregional, interregional, and overall differences within the Yellow River Basin were analyzed and delineated for the period from 2013 to 2022 (see Table 3). Regarding the overall differences, the coupling coordination level exhibited a fluctuating downward trend, peaking at a Gini coefficient of 0.139 in 2015, with fluctuations primarily occurring from 2015 to 2019, displaying a “V” shape of ascent and descent. The Gini coefficient from 2019 to 2022 shows a significant downward trend, indicating that although there are still differences between regions, under the deployment of the overall rural revitalization strategy, the implementation of policies aimed at promoting the coordinated advancement of agricultural land use and rural development in all regions has achieved some results. Consequently, the disparity in agricultural land use efficiency and the coupling and coordination of rural revitalization within the Yellow River Basin is gradually mitigated. Due to space limitations, the detailed analysis of intra-regional differences, inter-regional differences, and the contribution of regional differences can be found in Appendix 8.

The results of the regional difference analysis reveal that the interregional cross-effects of coupling and coordination of agricultural land use efficiency and rural revitalization in the Yellow River Basin are evident and exhibit an upward trend. For instance, the coupling coordination degree is notably greater in the downstream region than upstream and midstream regions. However, certain cities in the downstream region exhibit lower levels of coupling coordination than those in the upstream and midstream regions. Therefore, in future development planning, differentiated strategies should be implemented for cities at different levels. Specifically, the polarization of the core city should be mitigated through regional planning, such as developing symbiotic

agricultural zones, to foster complementary and synergistic industrial development between neighboring regions and the core city. Additionally, relatively backward cities should actively participate in regional development and play a key role in transferring agricultural industries from the core city and developed regions. By continuously narrowing the gap between city tiers, a strong foundation will be laid for the further enhancement of regional coupling coordination.

Discussion

The Yellow River Basin is one of the world's most agriculturally and rurally active regions. The coordination between improving agricultural land use efficiency and rural revitalization is critical in promoting the coordinated development of “population-land-industry” in rural areas. As a typical watershed with a gradient development paradigm, the research findings from this region can also offer insights into the agricultural and rural development of other basins. This study reveals that the coupling coordination between agricultural land use efficiency and rural revitalization in the Yellow River Basin has remained at the “grudging coordination” stage for an extended period. The development trend exhibits instability and significant regional disparities. The fluctuations in the level of coupling coordination are influenced by both the siphoning effect and the radiation effect. We provide an in-depth analysis of the potential causes of these phenomena.

The establishment of a coupling coordination mechanism within rural systems, with agricultural land use efficiency as the driving system, rural revitalization as the target system, and the coordinated development of “population-land-industry” as the intermediary, is crucial for promoting the sustainable development of agricultural production, the overall prosperity of the rural economy, and the significant improvement of farmers' living standards. Rural development has transcended the traditional model of relying solely on food trade, and this study argues that the improvement of agricultural land efficiency is aimed at maximizing the utility of agricultural land rather than being confined to crop cultivation alone⁵². For example, residents in Israel are actively utilizing agricultural land for non-traditional business activities in various sectors, including tourism, aquaculture, and freelancing⁴⁷. Similarly, Latvian smallholder farmers are focusing on diversifying economic activities on their farms⁷¹. These diversification strategies reflect farmers' rejection of short-term economic gains that compromise social equity and environmental sustainability, aligning with the broader goals of the rural revitalization strategy^{52,65}. However, it is important to acknowledge that the transformation of the agricultural production structure during non-grain production of agricultural land may result in environmental pollution, ecological damage, and other related issues, thereby affecting the sustainable development of agriculture and rural areas^{72,73}. At the same time, the lower and middle Mississippi River Basin faces significant challenges related to rural development imbalance⁷⁴. By exploring the coupling coordination relationship between agricultural land use efficiency and rural revitalization, this study, in conjunction with research related to the Mississippi River, provides empirical support for the sustainable agricultural and rural development of large-scale watersheds. Thus, the coupling coordination between agricultural land use efficiency and rural revitalization holds immense importance for the rural agricultural development of watersheds and offers valuable insights and lessons for the sustainable development of global agriculture and rural areas, particularly for developing countries transitioning from traditional to modern agriculture.

The coupling coordination level of cities in the Yellow River Basin exhibits a significant development gap, and this unbalanced development limits the coordination and sustainable development process across the basin's upper, middle, and lower reaches. A study of the Gandaki River Basin provides evidence that the upper, middle, and lower reaches of this basin face similar challenges to those in the Yellow River Basin—specifically, the structural framework of gradient development struggles to achieve the rational and sustainable flow of resource factors, leading to significant disparities in socio-economic and agricultural development levels within the basin⁷¹. Therefore, policymakers should embrace the concept of integrated basin development. Through unified planning and management, they can better coordinate resource utilization and environmental protection across the basin's regions, avoiding the contradictions arising from uneven development between different areas. Additionally, rational planning and differentiated policies should address regional development challenges. By implementing regional differentiation based on the concept of integrated watershed development, policymakers can ensure the sustainable development of the entire watershed while formulating targeted, flexible policies that address each region's specific needs and characteristics. This approach will help promote balanced regional development^{65,75}. Admittedly, implementing differentiated policies may face challenges in large river basins with complex natural conditions and significant regional disparities, such as the Yellow River Basin. For example, upstream regions must balance ecological protection with economic development, while financial constraints in technology promotion limit midstream regions. A dynamic monitoring mechanism is essential for managing uncertainties and enhancing policy adaptability in the policy implementation process. This can include implementing a classified response strategy—short-term adjustment, medium-term optimization, and long-term reconstruction—and establishing a participatory policy revision process involving “policy hearings, pilot verification, and full-scale promotion” to continuously improve policy instruments' flexibility, strengthening policies' dynamic adaptability.

Furthermore, the latecomer advantage of disadvantaged areas is often overlooked. The core of the latecomer advantage is to capitalize on time differences and information asymmetry, allowing latecomers to avoid the mistakes of their predecessors and directly adopt more effective development models⁷⁶. The upper reaches of the Yellow River Basin can leverage their “latecomer advantage,” leading to higher levels of factor resource agglomeration and return rates, which further contribute to a decline in the overall Gini coefficient. Studies in Porto, Bristol⁷⁷, and Ireland⁷⁸ have shown that disadvantaged cities often have higher levels of voluntary collaboration and cooperation, allowing them to participate more actively in development. Therefore, actively focusing on the “latecomer advantage” of disadvantaged areas is an important strategy for narrowing the gap

between the coupling coordination levels of agricultural land use efficiency and rural revitalization in the Yellow River Basin.

From a spatial perspective, the growth pole theory advocates prioritizing and concentrating resources to cultivate key growth poles, thereby promoting the overall development of a region through their leadership role. In practice, regional development is often driven by strengthening the growth of provincial capitals or core cities, and this approach is also applicable in the study of coupling coordination within the Yellow River Basin. This study reveals a significant spatial autocorrelation effect in the Yellow River Basin, with the spatial influence of cities exhibiting a higher level of coupling coordination (i.e., core cities) on neighboring cities being particularly prominent. According to the “Muldaur-Hirschman” model, the development of core cities about neighboring cities can generate both radiation and siphon effects, with the balance between these effects depending on their relative strength⁷⁹. Our study further emphasizes that the radiation effect of core cities in the Yellow River Basin on the coupling coordination level of neighboring cities is greater than the siphon effect. The mechanism by which the core city’s influence operates on neighboring regions is complex, and it is essential to accurately identify the conditions under which it manifests as either a siphon or a radiation effect, depending on the context. Some studies suggest that the relative strength of these effects changes with the stage of economic development: in the early stages, the siphoning effect prevails, exacerbating inter-regional disparities, while in more advanced stages of economic development, the radiation effect takes precedence, promoting economic convergence between regions⁸⁰. Another perspective considers the concentration of factors, suggesting that the growth pole effect continuously attracts population and industry, forming economic centers and producing a siphon effect on neighboring cities. However, when the concentration of factors reaches an excessive level and triggers the “crowding effect,” the impact on neighboring cities becomes a radiation effect⁸¹. Our study supports the second conclusion. In our study, the significant changes in spatial autocorrelation effects suggest that the siphoning effect may be weakened by the increase in overall positive agglomeration. Conversely, when agglomeration decreases, the siphoning effect may become more pronounced. This conclusion is quantitatively supported by the horizontal transfer probability test using the spatial Markov chain model, offering valuable insights into studying spatial spillover effects.

This study focuses on the Yellow River Basin as its object of analysis, emphasizing the coordination between individual basins and the cities within them through our analytical perspective and indicator system. It is important to note that the conclusions of this study are based on data availability and methodological assumptions. For instance, the assessment of agricultural land use efficiency does not account for natural factors, such as climate fluctuations, due to limitations in data availability, which may affect the generalizability of the results. A follow-up study will incorporate meteorological data and disaster risk assessments to enhance the multidimensionality of the efficiency indicators. Additionally, there may be a bidirectional causal relationship between agricultural land use efficiency and rural revitalization (efficient land use promotes rural revitalization, while rural industrial upgrading feeds back into land use optimization). However, this study’s coupled coordination degree model does not control for endogeneity, which may represent a potential research limitation. Finally, the study assumes that policies act independently on the coupling coordination degree. However, in reality, multiple policies (e.g., eco-compensation and digital countryside) may produce either synergistic or conflicting effects. Future studies could further investigate the cumulative effects of policies or the impact of major external shocks (e.g., COVID-19) using methods such as panel VAR models, scenario simulations, and others.

Conclusion and recommendation

This study focuses on agricultural land use efficiency and rural revitalization, using data from 82 cities in the Yellow River Basin between 2013 and 2022 as the research sample. By thoroughly explaining the coupling coordination mechanism between agricultural land use efficiency and rural revitalization, we analyze their coupling coordination characteristics across time and spatial dimensions, explore regional differences, and draw the following conclusions:

- (1) The coupling coordination level between agricultural land use efficiency and rural revitalization in the Yellow River Basin has remained at a “grudging coordination” stage and exhibits an unstable development trend. From 2013 to 2022, the level of coupling coordination between agricultural land use efficiency and rural revitalization shows a slight increase, but the overall development of both may approach a fragile equilibrium. The fluctuating characteristics of Moran’s *I* value and the misalignment between the policy framework and its objectives are potential causes of this phenomenon.
- (2) The cities in the Yellow River Basin are spatially interdependent. The core city radiates resources and economic vitality, driving the development of neighboring cities at the coupling coordination level, while the resource siphon effect remains relatively small. The characteristics of spatial dispersion suggest that core cities in the Yellow River Basin have a radiation effect in the development of coupling coordination. The “core-periphery” spatial pattern indicates the presence of a siphoning effect from core cities. When the spatial autocorrelation effect becomes more significant, the siphoning effect will likely be weakened by the overall enhancement of positive aggregation.
- (3) The interregional disparity between the upstream and midstream regions constitutes the primary factor contributing to the differences in coupling coordination levels within the Yellow River Basin. The overall gap in coupling coordination levels within the Yellow River Basin exhibits a fluctuating downward trend, while intraregional differences follow a spatial distribution pattern of “upstream > midstream > downstream.” The upstream regions, leveraging their “latecomer advantage,” are expected to exhibit higher concentrations of factor resources and higher rates of return. This, in turn, is anticipated to accelerate the decline of the overall Gini coefficient.

Building upon the conclusions above, to increase the coupling coordination of agricultural land use efficiency and rural revitalization in the Yellow River Basin and foster rural revitalization therein, the following recommendations are proposed:

- (1) Transforming the primitive development mode and fostering the sustainable development of rural revitalization. While the primitive mode of production may boost the region's economic output and development level in the short term, such growth comes at the expense of land use and rural agricultural development. Consequently, the Yellow River Basin should advocate for transforming its development mode and incorporating ecological security to enhance regional land use efficiency and environmental protection awareness. Simultaneously, the transformation of the economic development model should be ensured through systemic reform. Relevant departments should target the deficiencies of the agricultural land system in the Yellow River Basin, enhance reforms in the pertinent system, establish and refine the land transfer market, and facilitate accessible transfer channels. These measures aim to actualize rural revitalization by enhancing the quality and efficiency of development. Rural development will drive land-use improvements, enhance land-use efficiency, and ultimately establish a virtuous cycle between them.
- (2) Adhering to the concept of integrated basin development is crucial for addressing regional imbalance issues. With the implementation of agricultural and rural development policies, the coupling coordination gap between agricultural land use efficiency and rural revitalization in the Yellow River Basin has narrowed. However, polarization and regional imbalances persist. Therefore, policymakers should adopt an integrated approach and comprehensively evaluate the protection and development of the basin through top-level design and overarching goals. Provinces and cities in the Yellow River Basin should follow the principles of inter-provincial consultations, ecological co-management, region-wide co-construction, and shared development to ensure policy harmonization and synergies in implementation, ultimately narrowing the gap in coupling coordination levels. Specifically, regarding inter-provincial consultations, it is recommended that the government establish an inter-provincial cooperation committee for the Yellow River Basin and hold regular meetings to promote the synergistic development of water resources, land use, and rural revitalization. The agenda of these meetings should include assessment reports on the current status of water resources, land use, and rural revitalization in each province and city, with a strong focus on resource supply and demand, utilization efficiency, and the development of the rural economy. For ecological co-management, provinces and municipalities should collaborate to create a plan for the ecological protection of the watershed, including soil and water conservation, agricultural land protection, and other measures to ensure the health and stability of the watershed ecosystem. Regional cooperation projects should be promoted regarding region-wide co-construction, encouraging provinces and cities to jointly invest in infrastructure development, such as rural roads and irrigation systems, to improve overall agricultural land use efficiency and the distribution of agricultural products. In terms of development sharing, provinces and municipalities should work towards establishing special funds, such as the Yellow River Basin Development Fund and the Agricultural Land Use and Protection Fund, to support projects that improve agricultural land use efficiency and rural revitalization. These funds should subsidize the growth of agricultural cooperatives and local specialties, promote income growth for farmers, and ensure the rational distribution and effective use of resources to foster balanced regional development. To ensure the successful implementation of these measures, it is essential to create a unified policy standard system and a joint evaluation mechanism. This will enhance the synergy of policy implementation, prevent local conflicts of interest, improve the operability and efficiency of policy execution, and contribute to the integrated development and regional balance of the Yellow River Basin.
- (3) Emphasize regional differentiation policies, dynamic assessments, and adjustment measures. The coupling coordination between agricultural land use efficiency and rural revitalization in the Yellow River Basin's upper, middle, and lower reaches shows significant geographical variation. After the integrated development framework for the basin is established, differentiated policies should be implemented to address each region's unique natural conditions and socio-economic development levels. The upstream region (Qinghai, Gansu, and parts of Ningxia) faces arid soil, fragile ecology, and uneven water resource distribution challenges. With a weak economic base, a dependence on traditional agriculture for farmers' income, and limited application of modern technology, this region should integrate traditional and modern farming and animal husbandry practices. Efforts should focus on promoting eco-agriculture, strengthening ecological restoration and protection, and encouraging the adoption of modern agricultural technologies to transition from traditional to environmentally friendly agricultural practices. The middle reaches (Ningxia, Shaanxi, and Shanxi) experience severe soil erosion, agricultural surface pollution, and rapid economic growth yet have low levels of agricultural mechanization. This region should focus on rural revitalization with community participation, promote soil improvement techniques, such as cover cropping, enhance soil and water conservation, and implement sustainable agricultural production models. Additionally, investments in agricultural mechanization and technology application should be increased. The downstream region (Henan and Shandong) has fertile soil suitable for a wide range of crops, a strong economic base, and a high level of agricultural modernization. However, the region faces challenges like over-exploitation of water resources, pollution, and ecological pressure. To address these issues, the region should adopt a modern, market-oriented rural development model, embrace digitization, and advance agricultural modernization through technological innovation and smart agriculture. Promoting the deep processing and branding of agricultural products will also enhance market competitiveness. At the same time, relevant departments must continually track and evaluate the effectiveness of rural development policies in the Yellow River Basin. A statistical evaluation mechanism based on villages should be established. Big data and other net-

work technologies should be utilized to identify priorities for rural development and measure construction effectiveness accurately.

Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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Author contributions

S.L. and H.Z. conducted data analysis and edited the paper. S.L. and G.J. provided guidance on the methodology and analyzed the data. S.L. conceptualized the study. H.Z. and G.J. conducted the analysis on the evaluation of technology screening. S.L. and H.Z. contributed to article revisions. H.Z. conducted data analysis and visualization.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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