

Spatiotemporal Patterns and Driving Mechanisms of Coupling Coordination Between New-type Urbanization and Agricultural Modernization in the Yellow River Basin (Postprint)

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Abstract

Investigating the coupling and coordination relationship between new-type urbanization and agricultural modernization (the “two modernizations”) in the Yellow River Basin is of great significance for implementing the ecological protection and high-quality development strategy of the Yellow River Basin, and promoting urban-rural integration and coordinated regional development. An indicator system was constructed, and methods such as the entropy method, coupling coordination degree, and geographic detector were employed to quantitatively analyze the spatiotemporal patterns of the “two modernizations” levels and their coupling coordination in 67 prefecture-level cities in the Yellow River Basin from 2010 to 2022, and to explore the driving mechanisms. The results show that: (1) During the study period, the levels of the “two modernizations” in the Yellow River Basin increased significantly, both exhibiting a spatial distribution pattern of high in the east and low in the west. (2) The coupling coordination type of the “two modernizations” evolved from being dominated by near-disharmony to being primarily barely coordinated, with the scope of primary and intermediate coordination steadily expanding. (3) The coupling coordination level of the “two modernizations” shows significant spatial agglomeration characteristics, forming a prominent hotspot core in Shandong and two cold spot clusters in Shanxi, Gansu, and Ningxia (Gan-Ning). (4) The spatial differentiation pattern of coupling coordination development is the result of multi-factor synergistic effects and interactive influences. Economy, market, and digital finance are the core driving factors, agricultural technology and income are the secondary driving factors, and the interaction between transportation and other factors is significantly enhanced. The research findings help strengthen the theoretical understanding of the coupling of the “two modernizations” and provide policy references for the basin to promote the “two

modernizations” strategy and facilitate urban-rural integrated development.

Full Text

Spatio-temporal evolution and driving mechanism of coupling coordination between new urbanization and agricultural modernization in the Yellow River Basin

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Abstract

Exploring the coupled coordination relationship between new urbanization and agricultural modernization (the “two modernizations”) in the Yellow River Basin holds significant importance for implementing ecological protection and high-quality development strategies and for promoting urban-rural integration and coordinated regional development. This study constructs an indicator system and employs the entropy method, coupling coordination degree, and geographic detector methods to quantitatively analyze the spatio-temporal patterns and driving mechanisms of the “two modernizations” and their coupling coordination across 67 prefecture-level cities in the Yellow River Basin from 2010 to 2022. The results reveal four key findings: (1) During the study period, the level of the “two modernizations” in the Yellow River Basin increased significantly, both exhibiting an east-high, west-low spatial distribution pattern. (2) The coupling coordination type evolved from being dominated by near-disorder to being primarily characterized by reluctant coordination, with the scope of primary and secondary coordination steadily expanding. (3) The spatial agglomeration characteristics of the “two modernizations” coupling coordination are significant, forming an extreme hotspot core in Shandong and two cold-spot agglomeration areas in Gansu-Ningxia and Shanxi. (4) The spatial differentiation pattern of coupled and coordinated development results from the synergistic and interactive effects of multiple factors. Economy, market, and digital finance serve as core driving factors, while agricultural technology and income act as secondary drivers, and transportation significantly enhances its interaction with other factors. These findings strengthen theoretical understanding of the “two modernizations” coupling coordination and provide policy references for advancing the “two modernizations” strategy and promoting urban-rural integrated development in the basin.

Keywords: new urbanization; agricultural modernization; coupling coordination; spatio-temporal pattern; geographic detector; Yellow River Basin

Introduction

New urbanization represents a new starting point for urbanization research and practice in China, characterized by human-centeredness, synergy, inclusiveness, and sustainability. It emphasizes coordinated development among population, economy, society, and land subsystems. Agricultural modernization refers to the process and means of transforming traditional agriculture into modern agriculture. As key components of socialist modernization, new urbanization and agricultural modernization constitute important strategic fulcrums in the development of socialism with Chinese characteristics and provide core driving forces for regional coordinated development. The 18th National Congress of the Communist Party of China proposed following a path of “Four Modernizations” with Chinese characteristics, promoting mutual coordination between new urbanization and agricultural modernization and facilitating their synchronized development. The 14th Five-Year Plan for New Urbanization emphasizes adhering to a people-centered, four-modernizations-synchronized path of new urbanization with Chinese characteristics and insists on using urban development to drive rural development. During the symposium on ecological protection and high-quality development in the Yellow River Basin in 2019, General Secretary Xi Jinping stressed the need to coordinate new urbanization and rural revitalization in the Yellow River Basin to make greater contributions to advancing Chinese-style modernization. This series of policies all focuses on coordinated urban-rural development and vigorously promotes urban-rural integration. Therefore, exploring the spatio-temporal patterns and driving mechanisms of the “two modernizations” coupling coordination in the Yellow River Basin constitutes an important scientific issue. This research provides a theoretical dimension for thinking about urban-rural integrated development and holds significant practical importance for promoting high-quality development in the Yellow River Basin.

Existing research on the relationship and coupling coordination between new urbanization and agricultural modernization primarily focuses on three aspects. First, drawing on foreign experiences and exploring the relationship between the two. By reviewing the coordinated development process of urbanization and agricultural modernization in the United States, researchers have proposed experience references from the perspectives of behavioral agents, comparative advantages, and industrial chains. Studies suggest that the two are closely related, with agricultural modernization depending on and driving urbanization development, while new urbanization exerts a pulling effect on agricultural modernization. Second, quantitative evaluation of the coupling coordination level between new urbanization and agricultural modernization. Relevant studies have constructed multi-level evaluation systems for different spatial units, including the entire country, the Huang-Huai region, and Xinjiang, using comprehensive evaluation models such as fuzzy membership evaluation and the entropy method to quantify the “two modernizations” levels and identify their coupling coordination stages through coupling coordination degrees. However, few stud-

ies have used exploratory spatial analysis methods from geography to analyze the spatial heterogeneity of the “two modernizations” coupling coordination. Third, factor analysis. Some studies have employed linear regression, individual effect, and time effect models to explore influencing factors of the coordination among new industrialization, informatization, new urbanization, agricultural modernization, and greening (the “Five Modernizations”), finding that natural geographical environments and economic and social development differences jointly shape their spatial patterns. Education and technology positively impact the coordinated development of the “Five Modernizations,” while industrial levels and development intensity have negative effects. Other studies have used geographically weighted regression models to reveal that the main factors affecting the coordinated development efficiency of industrialization, informatization, urbanization, and agricultural modernization (the “Four Modernizations”) are per capita total investment in fixed assets in urban and rural areas and per capita GDP. Existing research has mostly focused on influencing factors of “Five Modernizations” synergy and “Four Modernizations” synchronization, with insufficient discussion on the driving mechanisms of “two modernizations” coordination in urban-rural systems. Fourth, problem identification and optimization pathways for “two modernizations” coordination. Existing research suggests that the “two modernizations” coordination process exhibits non-sustainable and uncoordinated phenomena, with prominent contradictions such as “dislocation” and “land competition” among agents. To address these issues and achieve coordinated development, studies have proposed optimization pathways and recommendations from three perspectives: industry-city integration, industry-agriculture mutual promotion, and urban-rural overall planning. These mainly include advocating for industry-city, population-city, and population-industry interactions; promoting agricultural efficiency, farmer income growth, and enterprise profit increases; establishing a long-term mechanism for mutual promotion of the “two modernizations” ; ensuring effective integration of agricultural modernization into the new urbanization process; and improving urban-rural circulation systems to achieve effective connection of production factors. Additionally, scholars have explored the impact of “two modernizations” coupling coordination on urban-rural income gaps in the central Guizhou urban agglomeration, finding a significant and strengthening effect.

In summary, research on the coupling coordination between new urbanization and agricultural modernization has yielded abundant results. However, studies at meso- and micro-scales such as cities and counties remain insufficient, particularly regarding the entire Yellow River Basin at the prefecture level. Research on influencing factors and driving mechanisms of the spatial differentiation patterns of their coupling coordination needs deepening, and quantitative studies from a geographical perspective on the driving mechanisms are rare. In 2019, ecological protection and high-quality development in the Yellow River Basin became a national strategy, making this research highly significant. The basin encompasses city clusters such as Lanzhou-Xining, Guanzhong Plain, Central Plains, and Shandong Peninsula, as well as major grain-producing areas like

Huang-Huai-Hai and Hetao, providing suitable conditions for studying the “two modernizations.” Therefore, this paper takes 67 prefecture-level cities in the Yellow River Basin as the research object, explores the spatio-temporal evolution of the “two modernizations” coupling coordination, and uses the geographic detector model to detect its driving mechanisms, aiming to provide policy references for different prefectures in the basin to comprehensively promote the “two modernizations” strategy and urban-rural integrated development.

1 Theoretical Framework for Coupling Coordination Between New Urbanization and Agricultural Modernization

New urbanization and agricultural modernization, as the two pillars of socialist modernization with Chinese characteristics, represent key strategic decisions driving urban-rural integrated development. The coupling coordination between new urbanization and agricultural modernization refers to the process in which the two subsystems and their internal elements interact, synergize, and promote urban-rural integrated development (Fig. [Figure 1: see original paper]).

Driving effects of new urbanization on agricultural modernization.

New urbanization promotes the development of secondary and tertiary industries, providing employment opportunities for rural surplus labor and increasing migrant workers’ income, which accumulates original capital for their return to hometowns to start businesses and develop modern agriculture. The living needs of urban residents and the rise of emerging business forms such as rural eco-tourism and agritainment expand market demand for agricultural and sideline products, accelerating agricultural modernization. As new urbanization advances, transportation between urban and rural areas improves, and public services such as education and medical care extend to rural areas, helping improve farmers’ quality, cultivate new-era farmers, and provide talent support for agricultural modernization. The radiation and trickle-down effects of new urbanization provide financial guarantees, technical support, and management experience for agricultural modernization, significantly improving agricultural production technology levels and economic benefits.

Agricultural modernization as the foundation and guarantee of new urbanization.

Through large-scale production, application of modern agricultural technologies, and practice of green ecological agriculture, agricultural modernization provides richer and greener agricultural and sideline products to meet urban residents’ diverse needs. Improved agricultural mechanization liberates large amounts of rural labor, providing human resources for new urbanization and promoting urban construction. Agricultural modernization increases grain yield per unit area and intensively utilizes agricultural land, supplying substantial development land for new urbanization. By optimizing agricultural structure, using modern agricultural technologies, and developing ecological and circular agriculture, agricultural modernization improves resource utilization efficiency, enhances the ecological environment, and lays an ecological foundation for sustainable urban-rural system development.

New urbanization and agricultural modernization achieve synergistic development through factor complementarity, industrial interaction, and cultural integration, while relying on government policy guarantees and market regulation mechanisms to ensure steady progress in their coupling coordination.

2 Data and Methods

2.1 Study Area

The Yellow River Basin spans nine provinces (autonomous regions), covering a drainage area of 7.958×10^4 km² with a total population of 4.19×10^8 and a GDP of 3.07×10^{13} yuan, accounting for 29.73%, 25.37%, and 62.13% of the national totals, respectively. The urbanization rate reached 62.13% in 2022. The basin encompasses five national-level city clusters including Shandong Peninsula and major grain-producing areas such as Henan and Shandong provinces. It is home to 1,240 national-level leading agricultural industrialization enterprises and the Yangling National Agricultural High-tech Industry Demonstration Zone. Due to differences in resource endowments, natural conditions, and transportation location, development across the upper, middle, and lower reaches is unbalanced, with significant variations in new urbanization and agricultural modernization levels among provinces and cities. Given that in 2016, Hulunbuir and Tongliao in Inner Mongolia were incorporated into the Northeast Revitalization Strategy, and Sichuan was included in the Yangtze River Economic Belt Strategy (with the Yellow River only flowing through Aba Tibetan and Qiang Autonomous Prefecture and Garzê Tibetan Autonomous Prefecture in Sichuan), this study defines the research area as the Yellow River Basin excluding Sichuan and eastern Inner Mongolia. Based on data availability, the final research scope includes 67 prefecture-level cities in the Yellow River Basin (Fig. [Figure 2: see original paper]).

2.2 Index System Construction

The traditional land-centered urbanization model has led to negative impacts such as loss of cultivated land resources, emergence of ghost cities, intensified heat island effects, and posed enormous challenges to coordinated urban-rural development, causing imbalanced income growth between urban and rural residents and significant rural hollowing. New urbanization adheres to a people-centered concept, optimizes urbanization spatial layout, accelerates modernization of urban governance systems and capabilities, and emphasizes urban-rural integration while stressing ecological civilization importance. Drawing on existing research and combining the connotation of new urbanization with the guidelines and specific measures of the “14th Five-Year Plan for New Urbanization Implementation,” this study constructs an evaluation index system for new urbanization in the Yellow River Basin from five dimensions: population, economy, society, space, and ecology, based on scientific principles and data availability.

Agricultural modernization is a dynamic concept, with historically significant technological progress driving its evolution and enriching its connotation over time. The core orientation of agricultural and rural modernization is to integrate cutting-edge technologies, modern equipment, and advanced management concepts into agriculture, extend infrastructure construction and basic public services to rural areas, thereby improving agricultural production efficiency, beautifying rural environments, enhancing farmers' quality of life, and promoting comprehensive agricultural upgrading, rural development, and farmer progress. Therefore, referencing previous studies and combining the connotation of agricultural modernization with the requirements, strategic orientation, and initiatives of the "14th Five-Year Plan for Agricultural and Rural Modernization," this study constructs an evaluation index system for agricultural modernization in the Yellow River Basin from five dimensions: agricultural input level, agricultural output level, rural social development level, agricultural industrialization, and agricultural sustainability (Table).

2.3 Methods

2.3.1 Entropy Weight Method and Coefficient of Variation Method

The entropy weight method determines weights based on the information entropy of evaluation indicators, while the coefficient of variation method uses information contained in indicators to quantify their variation coefficients for weight assignment. Both are typical objective weighting methods that avoid subjectivity and enhance scientific accuracy. Therefore, this study employs a combination of entropy weight method and coefficient of variation method to measure the "two modernizations" level in the Yellow River Basin. First, indicators are normalized; second, weights are obtained using both methods; then, combination weights are calculated using arithmetic averaging; finally, the "two modernizations" level is derived using the comprehensive development index.

2.3.2 Coupling Coordination Degree Model The coupling coordination degree model is currently used to measure the interaction efficiency and coordination level of two or more systems, primarily including coupling degree and coupling coordination degree. Therefore, this study adopts the coupling coordination degree model to judge the interactive coupling coordination degree of the "two modernizations." Referencing previous research and considering the coupling coordination level of the "two modernizations" in the Yellow River Basin, the coupling coordination degree types are classified as shown in Table .

2.3.3 Global Spatial Autocorrelation Tobler proposed the First Law of Geography—spatial autocorrelation—which states that everything is related to everything else, but near things are more related than distant things. This study uses the global Moran's I index to identify spatial distribution characteristics and agglomeration of the "two modernizations" coupling coordination development level in the Yellow River Basin.

2.3.4 Cold and Hot Spot Analysis Cold and hot spot analysis can detail the hotspot areas (high values) and cold spot areas (low values) of factor agglomeration. Therefore, this study uses the Getis-Ord G^* index to measure the spatial distribution of hotspots and cold spots of the “two modernizations” coupling coordination degree in the Yellow River Basin. The calculation formula is:

$$G_i^*(d) = \frac{\sum_{j=1}^n w_{ij}(d)x_j}{\sum_{j=1}^n x_j}$$

where d is the distance threshold, n is the number of regions, w is the spatial weight matrix, and x is the observed value of region unit i . When $G^*(d)$ is significantly positive, it indicates that the values around region i^* are relatively high, making the region a hotspot area, which suggests high-value agglomeration of the “two modernizations” coupling coordination degree; conversely, it is a cold spot area, indicating low-value agglomeration distribution.

2.3.5 Geographic Detector (1) Optimal parameter selection. The geographic detector is a model for analyzing spatial differentiation patterns and their driving mechanisms. Its application effectiveness depends on the optimal scale of stratified heterogeneity during spatial data discretization. This study uses the quantile method in ArcGIS to classify driving factors of the “two modernizations” coupling coordination development in the Yellow River Basin, selecting the spatial scale with the maximum q value as the parameter for geographic detector analysis.

(2) Geographic detector method. Based on the selected optimal parameters, factor detection and interaction detection in the geographic detector are employed to analyze the core driving factors of the spatial differentiation pattern of the “two modernizations” coupling coordination degree and their interactive effects. The q value represents the explanatory power of factors, calculated as:

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

where q is the explanatory power of the factor with a value range of $[0, 1]$; the closer to 1, the greater the explanatory power; $h = 1, 2, \dots, L$ represents the strata of the explanatory or explained variable; N and N are the number of units in stratum h and the entire city area, respectively; and σ^2 and σ^2 are the variances of stratum h and the entire city area, respectively. The principles, type classification, and discrimination methods of the interaction detector are detailed in relevant literature.

2.4 Data Sources

Statistical data were obtained from the *China City Statistical Yearbook* and *China Urban-Rural Construction Statistical Yearbook* (2011-2023), as well as provincial and municipal statistical yearbooks and statistical bulletins of the study area. Additional data sources include the CNKI yearbook database, the second and third national land survey data, some agricultural census bulletins, and the sixth and seventh national population census data. Data on geographical indication agricultural products were obtained from the National Geographical Indication Agricultural Products Query System. The number of national-level agricultural science and technology parks was obtained from lists published by the Ministry of Science and Technology. Data on national key leading enterprises in agricultural industrialization were obtained from the Ministry of Agriculture and Rural Affairs' 1st-9th batch of data, with enterprise registration locations parsed using the Qichacha website. Normalized Difference Vegetation Index (NDVI) data were obtained from the National Tibetan Plateau Data Center. The digital inclusive finance index was sourced from the *Peking University Digital Inclusive Finance Index*. Missing data for some years were supplemented using interpolation methods.

3 Results

3.1 Spatio-temporal Evolution Characteristics

3.1.1 Spatio-temporal Evolution of New Urbanization and Agricultural Modernization Levels During the study period, the “two modernizations” levels in the Yellow River Basin increased significantly. The new urbanization level mean value rose from 0.23 to 0.51, while the agricultural modernization level increased from 0.18 to 0.68, with a growth rate as high as 278%. Although the growth rate of new urbanization was lower than that of agricultural modernization, the standard deviation and variance of both levels continued to increase, indicating widening regional gaps and a growing “Matthew effect.” This demonstrates both the phased achievements of urban-rural integration in the Yellow River Basin and the urgent need for cross-regional coordination mechanism construction.

The spatial differentiation of the “two modernizations” levels is significant. The new urbanization level shows an east-high, west-low distribution, with high-value areas consistently located in Qingdao, Jinan, Zhengzhou, Xi'an, and other provincial capitals, while low-value areas are concentrated in western Qinghai, Gansu, Ningxia (Qing-Gan-Ning), and the Qinba Mountain area. This may be attributed to the relatively developed economy, superior location, and complete infrastructure in Shandong's coastal areas and provincial capitals, while western regions are constrained by natural conditions, economic backwardness, inconvenient transportation, and lack of non-agricultural industries. The agricultural modernization level also exhibits an east-high, west-low differentiation pattern (Fig. [Figure 3: see original paper]). High-value areas are consistently located in

the three major core areas of Shandong, Henan, and Guanzhong Plain, as well as the Yellow River “Ji Zi Wan” region, likely due to superior natural conditions (flat terrain, etc.), long agricultural history, high mechanization levels, and status as nationally important agricultural belts. Low-value areas are distributed in parts of western Shanxi, northern Shaanxi, and Gansu-Ningxia, constrained by terrain, climate, location, and other factors.

3.1.2 Spatio-temporal Evolution of Coupling Coordination During the study period, the “two modernizations” coupling coordination degree in the Yellow River Basin continued to rise, increasing from 0.35–0.60 to 0.51–0.77, with standard deviation and variance synchronously increasing, indicating growing inter-city gaps and prominent regional lock-in effects. Although some areas achieved intermediate coordination levels, the overall state remained near-disorder and reluctant coordination (Fig. [Figure 4: see original paper]).

Viewed by year, in 2010, the “two modernizations” coupling coordination degree was dominated by near-disorder. Mild disorder areas were distributed in western cities such as Baiyin and Tongchuan, whose weak economic foundations, gradually depleted resources, and severe population loss exemplify the predicament of ordinary prefecture-level cities. Near-disorder areas were widely distributed across most regions of Qinghai, Ningxia, Shaanxi, Shanxi, Henan, and Shandong. Reluctant coordination areas were mainly concentrated in eastern Shandong and cities such as Zhengzhou, Xi’ an, and Taiyuan, mostly economically developed provincial capitals with large populations. Only Qingdao reached primary coordination level.

By 2016, the “two modernizations” coupling coordination degree shifted to reluctant coordination as the dominant type, with its distribution range expanding and near-disorder areas shrinking; mild disorder areas disappeared. Primary coordination areas expanded to Qingdao, Jinan, Yantai, Zhengzhou, and other cities, with spatial distribution changing from point-like to patchy.

By 2022, reluctant coordination remained dominant across the entire basin. Primary coordination areas increased to 13 cities, with Jinan, Qingdao, Yantai, Zhengzhou, and other 9 cities entering intermediate coordination stage, indicating tight interdependence and parallel development momentum in these locations. The overall pattern showed “east-high, west-low, with prominent northwest,” forming a continuous low-value area in eastern Gansu and Zhongwei in the upper reaches, while high-value areas presented a single-core pattern centered on Qingdao, with Zhengzhou, Xi’ an, and other cities scattered in between.

3.1.3 Spatial Agglomeration Characteristics The global Moran’ s I index for the “two modernizations” coupling coordination degree in the Yellow River Basin continued to increase from 2010 to 2022, all passing significance tests (Table), indicating significant positive spatial correlation between cities’ coupling coordination levels and their neighboring cities, with strengthening spatial spillover effects. Therefore, the cold and hot spot method was further used

to explore spatial agglomeration characteristics and clustering patterns. Using ArcGIS 10.8 software's G^* analysis tool, the cold and hot spot distribution maps of the “two modernizations” coupling coordination degree were drawn (Fig. [Figure 5: see original paper]).

The hotspot center of the Yellow River Basin is concentrated in Shandong, while cold spot areas gather in Gansu-Ningxia, with both showing contiguous distributions and a few scattered areas. Specifically, in 2010, there were 6 hotspot cities concentrated in the Shandong Peninsula and 5 cold spot cities distributed in upper-reach Gansu and Wuzhong, Zhongwei in Ningxia. By 2016, hotspot cities expanded to include Liaocheng and Zaozhuang in Shandong, with high-value areas moving westward; cold spot cities increased to 8, adding Yuncheng, Lüliang, and Jinzhong in Shanxi, with low-value areas expanding eastward. By 2022, hotspot cities further increased, covering 13 cities in Shandong and Puyang on the Henan-Shandong border, forming an extreme core; cold spot areas further expanded, adding Haidong in upper-reach Qinghai and Taiyuan in middle-reach Shanxi, strengthening low-value area agglomeration in the upper and middle reaches and forming two cold spot agglomeration areas in Shanxi and Gansu-Ningxia. This may be attributed to Shandong's coastal economic advantages, strong industrial foundation, and high technological investment forming a virtuous cycle for “two modernizations” coordinated development, while Gansu-Ningxia and Shanxi are constrained by ecological fragility, economic lag, innovation deficiency, and resource-based industry dominance, resulting in weaker urban-rural synergy and lagging “two modernizations” coupling coordination.

3.2 Driving Mechanism Analysis of Spatial Differentiation Patterns

3.2.1 Selection of Influencing Factors New urbanization and agricultural modernization have a close and objective “symbiotic relationship” with mutually promoting and co-evolving attributes. Therefore, their coupling coordination development is inevitably influenced by multiple systems and various aspects. Referencing existing research and considering the actual conditions of the Yellow River Basin, this study constructs an indicator system affecting the “two modernizations” coupling coordination from economic, market, digital finance, transportation, opening-up, innovation, and other dimensions (Table).

3.2.2 Factor Detection Results To analyze the driving factors of the spatial differentiation pattern of the “two modernizations” coupling coordination degree in the Yellow River Basin, factor detection was conducted for influencing factors from 2010, 2016, and 2022 (Table). The results show that all indicators passed significance tests at the 5% level or above, indicating that the selected driving factors can well explain the spatial differentiation pattern.

Specifically, in 2010, factors ranked by explanatory power were: $eco > mar > dfin > inno > gov > open > inco > atech > tra > pop$, indicating that economic development, market consumption, and digital finance are core driving factors for “two modernizations” coupling coordination development. The explanatory

power of influencing factors changed differently during the study period, with rankings shifting. Opening-up and transportation rose by 2 and 1 positions respectively, indicating their strengthening explanatory power and 不断增强 influence on the spatial differentiation of “two modernizations” coordination in the Yellow River Basin. This is because cities in the basin have leveraged the Western Development Strategy and the Belt and Road Initiative to improve opening-up levels, while national and local governments continuously improve highways and other infrastructure, such as the “Village-to-Village” project and “Last Mile” initiatives, increasing urban-rural development impacts. Although digital finance and government rankings declined, they remained major driving factors.

In 2022, the explanatory power of most influencing factors continued to rise, while some declined (Table). Government and agricultural technology showed significant increases in explanatory power, indicating that enhanced government regulation capacity and agricultural mechanization development (which liberates rural labor to support urban development) have strengthened the promoting effect on “two modernizations” coordination. Innovation and income showed relatively obvious declines in explanatory power, indicating weakened impacts, possibly due to economic development and industrial transformation upgrading, with population continuously flowing into secondary and tertiary industries and employment structures increasingly converging, consistent with Petty-Clark’ s Law.

In summary, although factor rankings changed during the study period, economy, market, digital finance, opening-up, and government consistently dominated, representing the main driving forces affecting the spatial pattern evolution of “two modernizations” coupling coordination in the Yellow River Basin. The increasing explanatory power of agricultural technology indicates its growing importance and suggests it may become a crucial factor influencing “two modernizations” coupling coordination in the future. Population explanatory power continuously declined, with weakening influence.

3.2.3 Interaction Detection Results To explore the interactive effects among driving factors of “two modernizations” coupling coordination in the Yellow River Basin, interaction detection was conducted for influencing factors from 2010, 2016, and 2022. Using Origin software to generate heatmaps (Fig. [Figure 6: see original paper] and Fig. [Figure 7: see original paper]), the interactive driving effects are visually displayed at different levels.

The interaction effects of influencing factors in 2010, 2016, and 2022 all fell into two categories: double-factor enhancement and nonlinear enhancement, with no weakening or independent effects. This indicates that the spatial differentiation pattern of “two modernizations” coupling coordination level in the Yellow River Basin results from synergistic and interactive influences among economic, market, government, and other factors.

From specific influencing factors, the most prominent interactions in 2010 were income atech, dfin atech, and gov dfin; in 2016, they were gov tra, open mar, and open atech; in 2022, they were atech dfin, open atech, and tra pop. The interactions of digital finance, opening-up, and market with other factors consistently ranked high, indicating that these three factors not only have strong single-factor explanatory power but also dominate in two-factor interactions, significantly influencing the improvement of “two modernizations” coupling coordination in the Yellow River Basin through interaction with other factors. The interaction effects of transportation and agricultural technology with other driving factors significantly enhanced, indicating they effectively strengthen other factors’ impacts on “two modernizations” coupling coordination development. Income and population had low single-factor explanatory power and weak impacts on “two modernizations” coupling coordination development, but their explanatory power significantly increased after interaction, becoming a non-negligible force driving “two modernizations” coupling coordination development. Their interactions with other factors are equally important and jointly affect “two modernizations” coupling coordination development.

4 Conclusions and Recommendations

4.1 Conclusions

This study uses the entropy method and coefficient of variation method for combined weighting to analyze the “two modernizations” development level in the Yellow River Basin, employs coupling coordination degree, spatial autocorrelation, and cold-hot spot analysis to examine spatio-temporal patterns and spatial agglomeration characteristics of “two modernizations” coupling coordination, and further applies the geographic detector to explore the driving mechanisms. The main conclusions are as follows:

- (1) **Temporal evolution:** From 2010 to 2022, the “two modernizations” levels in the Yellow River Basin increased significantly overall. **Spatial pattern:** The “two modernizations” levels showed significant spatial differences, both exhibiting an east-high, west-low distribution. The “two modernizations” coupling coordination degree continuously improved, evolving from being dominated by near-disorder to being primarily characterized by reluctant coordination, with the scope of primary and intermediate coordination steadily expanding. The coupling coordination degree showed an “east-high, west-low, with prominent northwest” pattern, forming a continuous low-value area composed of Longdong and Zhongwei in the upper reaches, while high-value areas presented a single-core pattern centered on Qingdao, with Zhengzhou, Xi’an, and other cities scattered in between.
- (2) The “two modernizations” coupling coordination level in the Yellow River Basin shows significant positive spatial correlation, with continuously strengthening spatial autocorrelation. The hotspot and cold spot areas showed obvious diffusion, with hotspot cities expanding from 6 to cover 13

cities in Shandong and Puyang on the Henan-Shandong border, and cold spot cities expanding from upper-reach Gansu-Ningxia to middle-reach Shanxi, ultimately forming an extreme hotspot core in Shandong and two cold spot areas in Shanxi and Gansu-Ningxia.

- (3) The spatial differentiation pattern of “two modernizations” coupling coordination level results from synergistic and interactive effects among economic, market, digital finance, opening-up, government, and other factors. From factor detection, economy, market, and digital finance are core driving factors, while agricultural technology, population, and income are secondary drivers. Economy and market have strong impacts on “two modernizations” coupling coordination, with consistently high explanatory power. Digital finance and population showed declining then rising explanatory power, while agricultural technology and government significantly enhanced their roles. From interaction detection, the interactive effects of influencing factors are mainly double-factor enhancement and nonlinear enhancement, with explanatory power significantly increasing after interaction among different factors, showing synergistic enhancement effects. The interactions of digital finance, opening-up, and market with other factors are prominent, and the interaction effects of transportation with other factors significantly enhance, indicating they effectively strengthen other factors’ impacts on “two modernizations” coupling coordination development.

Compared with existing research, this study, based on the “pattern-process-mechanism” geographical research paradigm and from a geographical perspective, uses the geographic detector to explore the driving mechanisms of the spatial differentiation pattern of “two modernizations” coupling coordination in the Yellow River Basin from economic, market, population, innovation, and other aspects. Economic level differences lay the foundation for coupling coordination, market consumption strengthens supply-demand regulation through digital finance empowerment, and synergistically pushes extreme cores, representing the core driving force shaping the spatial differentiation characteristics of “east-high, west-low” and “concentrated hotspots.” This research clarifies the driving mechanism of “two modernizations” coupling coordination, enriches relevant achievements, and provides strong theoretical support for future policy formulation and practical operations.

4.2 Recommendations

This paper proposes the following policy implications to promote coordinated “two modernizations” development in the Yellow River Basin:

- (1) **Deepen high-quality new urbanization development**, emphasizing coordinated development among population, economy, society, space, and ecology subsystems. Cities with higher new urbanization levels such as Qingdao, Jinan, Zhengzhou, and Xi’an should consolidate existing foun-

dations, strengthen innovation leadership, accelerate modern industrial system transformation, and optimize territorial space development and protection. Ordinary prefecture-level cities in upper-reach Gansu-Ningxia and middle-reach Qin-Jin regions should leverage their resource endowments, cultivate characteristic industry clusters, actively undertake industrial transfers through the Belt and Road Initiative and national policy inclinations toward central and western regions, and build talent attraction mechanisms.

- (2) **Deepen agricultural supply-side structural reform**, construct a green ecological modern agricultural system, and promote agricultural modernization quality and efficiency improvement. Qinghai, Gansu, and Ningxia can utilize their unique resource conditions to focus on developing characteristic planting, facility agriculture, and animal husbandry; Shanxi and Shaanxi can rely on cultural resources to promote culture-tourism integration, providing farming experience activities for tourists through rural tourism and developing eco-tourism agriculture; Henan and Shandong, as major agricultural provinces, should develop modern, mechanized agriculture to ensure agricultural and sideline product supply and strengthen national food security strategic support.
- (3) **Implement the “two modernizations” coordination strategy**, optimize and improve urban-rural integration mechanisms, and narrow urban-rural and regional gaps. Clarifying the driving mechanism of “two modernizations” coordination in the Yellow River Basin, the core driving roles of economy, market, government, and other factors should be leveraged, along with the interactive effects of digital finance, opening-up, and other factors with other influencing factors, to promote “two modernizations” coordinated development. Strengthen downstream-to-upstream technology transfer and compensation, build a “financial bond + policy guarantee”三位一体 (trinity) basin “two modernizations” collaborative governance framework to achieve coordinated development between downstream extreme cores and upstream cold spots. Governments need to improve regional coordination policies, break down interest barriers and policy barriers between regions, promote rational flow of all factors, and build a multi-pole linked basin development pattern. Deepen the rural revitalization strategy, effectively leverage the synergistic effect of the “two modernizations,” promote urban-rural integrated development, and jointly build a new chapter of high-quality development in the Yellow River Basin.

This study still has certain limitations requiring further exploration. First, due to data availability, the sample size does not cover all prefecture-level cities in the Yellow River Basin, and the indicator evaluation system may need further improvement. Future research could utilize multi-source data such as nighttime light remote sensing data, municipal construction land imagery, and big data to enrich data volume and sample size and enhance scientific robustness. Second, in the era of informatization and artificial intelligence, future studies could attempt

to use machine learning to predict the coupling coordination degree of the “two modernizations.”

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