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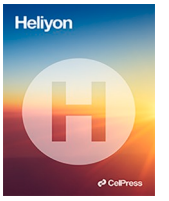

Coupling coordination analysis of population, economy and grain in major grain-producing counties

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ABSTRACT

This study discusses the coupling and coordination relationship among population, economy, and grain production in the central primary grain-producing counties. It aims to find a dynamic balance between the responsibility of the grain-producing areas in ensuring food security and the development of the economy and population. This study focuses on the main grain-producing provinces of Jilin and Jiangsu in China. Based on county-level data on population, economy, and grain production, it constructs an index system for the population, economy, and grain systems. The study employs the entropy weighting method and coupling coordination model to analyze the coupling coordination degree and coordinated development of the three systems in Jilin and Jiangsu provinces from 2000 to 2020, covering a span of 21 years. The coupling coordination degree and coordinated development of the three systems in the main grain-producing areas have gradually moved towards high-quality coordination. In the economically underdeveloped province of Jilin, factors such as geographical environment, population size, and industrial structure impose constraints on system coordination. In the economically developed region of Jiangsu, there is a high labour force and better development of the secondary and tertiary industries, but relatively less investment in agriculture, which affects overall coordination. It is necessary to promote regions' development with high-quality coordination by leveraging their advantages in economic foundations, and further advance the construction of the main grain-producing areas. Additionally, efforts should be made to strengthen policy support for underdeveloped regions, clearly define the industrial types and positioning of counties, and focus on industrial transformation and upgrading.

1. Introduction

China is committed to comprehensively consolidating the foundation of food security and establishing a sound mechanism for compensating the interests of major grain-producing areas. The counties within the grain-producing regions are the main contributors to grain production, and their level of economic development and total population play a crucial role in enhancing the comprehensive production capacity of grain. The Chinese government has emphasized the need to vigorously develop industries that benefit the local people in counties [1], support the extension of industries from large and medium-sized cities to counties [2], strengthen the construction of commercial systems in counties [3], and promote the upgrading of rural consumption [4,5]. It also encourage rural

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residents to start businesses and seek employment locally [6–8], with counties as nodes, providing high-quality job opportunities for the surrounding farmers [9,10]. The development of population and economy are closely intertwined, and population's sustained and normal growth is an important driving force for economic development [11]. From the perspective of input factors, the labour force is the fundamental basis for grain production [12–19]. The coordinated and harmonious development of the economy [20–23], population [24–29], and grain production [30–36]can significantly enhance the overall strength of grain-producing counties in the main grain-producing regions. Currently, there is relatively limited attention from scholars regarding the coupling and coordination among population, economic development, and grain production in grain-producing counties within the major grain-producing regions [37–40]. The cases analyzing the coordination among the three factors have primarily focused on single provinces. China has a total of 13 major grain-producing regions, and there are significant differences in resource endowments between these regions [41]. Additionally, the development levels within each region are also diverse [42]. By conducting a comparative analysis of the coupling and coordination status among population, economic development, and grain production in grain-producing counties with different resource endowments, it is possible to provide more targeted policy recommendations for developing grain-producing counties within the significant grain-producing regions. This can help improve the level of food security and promote the realization of shared prosperity.

Since the 1980s, the economic growth of Jilin Province has been gradually slowing down [43,44], and its county-level development started later compared to the eastern coastal provinces. Jilin Province faces increased downward pressure on its economy and challenges such as population outflow [45–47]. In the future, it will also face a series of daunting tasks, including industrial transformation and the crucial responsibility of ensuring national food security. Jiangsu Province is located in China's vital core region of the Yangtze River Delta. It is a significant economically developed area and also one of the major grain-producing regions. While Jiangsu Province has achieved economic development [48], it also faces challenges such as intensified conflicts between population and land [49], loss of agricultural labour force [50], and expansion of non-agricultural land [51–55]. In comparison, in 2020, Jiangsu Province had a total population of 84.77 million people, while Jilin Province had a population of 23.99 million. The gross domestic product (GDP) of Jiangsu Province was more than four times that of Jilin Province. In terms of grain production, the difference between the two provinces is not significant. Based on population theory and theories related to regional industrial structure, this study considers the practical development of grain-producing counties within the significant grain-producing regions. It constructs an evaluation index system for the coupling and coordinating population, economy, and grain production in grain-producing counties. By comprehensively analyzing the coupling and coordination relationships and their spatiotemporal evolution using multiple indicators, this study aims to provide policy references for consolidating the foundation of food security and establishing a sound mechanism for compensating the interests of grain-producing counties within the major grain-producing regions.

2. Methods

2.1. Indicator selection significance and system construction

In accordance with the principles of comparability and scientific rigour, and taking into account the specific circumstances of Jilin Province and Jiangsu Province, this study constructs the population system, economic system, and grain system [13,45,56]. The

Table 1
Population-economy-food coupling and coordination system indicator framework.

System	Indicator Types	Indicator	Positive and Negative Direction
population system	population level	Total Population (in tens of thousands)	+
		Population Density (people per square kilometer)	+
		Population in Primary, Secondary, and Tertiary Industries (in tens of thousands)	+
		Sex Ratio (%)	–
		Urban Population Ratio (%)	+
	Medical Facilities	Medical and Health Institution Personnel (people)	+
		Total Hospital Beds (beds)	+
economic system	Economic Aggregate	Gross Domestic Product (GDP) (in ten thousand yuan)	+
		Local Fiscal Revenue (in ten thousand yuan)	+
		Local Fiscal Expenditure (in ten thousand yuan)	+
	Economic Level	Per Capita GDP (in yuan)	+
		Per Capita Local Fiscal Revenue (in yuan)	+
		Per Capita Local Fiscal Expenditure (in yuan)	+
	Economic Factors	Total Exports (in ten thousand yuan)	+
		Total Retail Sales of Consumer Goods (in ten thousand yuan)	+
	Economic Structure	Value Added of the Primary Industry (in ten thousand yuan)	+
		Value Added of the Secondary Industry (in ten thousand yuan)	+
		Value Added of the Tertiary Industry (in ten thousand yuan)	+
		Total Industrial Output Value (in ten thousand yuan)	+
grain system	Grain Production	Total Grain Production (in tons)	+
		Per Capita Grain Production (in tons)	+
		Land Development Rate (%)	+
	Input Factors	Chemical Fertilizer Use per Unit of Cultivated Land (in tons)	+
	Planting Area	Grain Cultivation Area (in square kilometers)	+

population system includes indicators such as population level, labour force population, gender structure, urban-rural structure, and medical facilities. The economic system includes indicators such as economic aggregate, economic level, and economic structure of factors. The grain system includes indicators such as grain production, input factors, and planting area. The frequency statistics method was used to select indicators for the population system, economic system, and grain system. Ultimately, a total of 24 indicators were selected to form the population system, economic system, and grain system (see Table 1).

In the population system, the population level is reflected by the total population and the sex ratio, which represent the essential characteristics of the population in each county or city. The impact of the labour force population on the population system is represented by the sum of employment in the primary, secondary, and tertiary industries. The urbanization rate is calculated as the ratio of the urban population to the total population. Since both Jilin Province and Jiangsu Province face the issue of population ageing, the number of medical institutions and total hospital beds are chosen to reflect the medical facilities. The economic system selects the total GDP, local fiscal revenue, and local fiscal expenditure to represent the economic aggregate. Per capita GDP, per capita local fiscal expenditure, and per capita local fiscal revenue are chosen to reflect the economic level of each county or city. Social fixed asset investment, total exports, and total retail sales of consumer goods are selected as indicators of economic development factors. The value-added of the primary, secondary, and tertiary industries and industrial output value are selected to reflect the economic structure. In the grain system, the total grain production, per capita grain production, and the land development rate are chosen to reflect the grain production situation. Chemical fertilizers per unit of cultivated land are used to represent input factors. The area of grain cultivation is selected to reflect land input.

2.2. Data source

Based on the county-level administrative divisions of Jilin Province and Jiangsu Province in 2020, Jilin Province currently has 20 counties, 16 counties, and 3 autonomous counties, while Jiangsu Province has 21 counties and 19 counties. To ensure the matching of population, economy, and grain systems, the corresponding editions of the "Statistical Yearbook of Jilin Province," "Statistical Yearbook of Jiangsu Province," "China City Statistical Yearbook," and "China County Statistical Yearbook" for the respective years were used as data sources.

2.3. Weighting of indicators

The entropy weight method is an objective weighting approach that utilizes the entropy principle to determine the indicators' dispersion level. A higher level of dispersion indicates a more significant disorder in the system; thus, the corresponding indicator significantly influences the comprehensive evaluation.

Firstly, due to the differences in units and variations among different variables, the coefficients of some variables may become difficult to interpret in practical terms. Therefore, in order to address the influence of dimensionality and variation on the numerical values, it is necessary to standardize the data. This study uses the extrema method to transform the original data linearly. Specific formulas are applied separately for positive and negative indicators.

Positive Indicators:

$$A_{ef} = \frac{a_{ef} - min(a_f)}{\max(a_f) - \min(a_f)} \tag{1}$$

Negative Indicators:

$$A_{ef} = \frac{\max(a_f) - a_{ef}}{\max(a_f) - \min(a_f)} \tag{2}$$

Among them, a_{ef} represents the actual value of the f th evaluation indicator for the e th evaluation object; $\max(a_f)$ represents the maximum value among the f th evaluation indicator; $\min(a_f)$ represents the minimum value among the f th evaluation indicator; A_{ef} represents the standardized value of the indicator after normalization processing.

After standardizing the data, the next step is to calculate the weight of the sample value for the e th evaluation object under the f th indicator.

$$E_{ef} = \frac{a_{ef}}{\sum_{e=1}^{n} a_{ef}} (e = 1, 2, \ldots, n; f = 1, 2, \ldots, m) \tag{3}$$

Next, the entropy G_f for the fth indicator is calculated using the entropy calculation f ormula.

$$G_f = -l \sum_{e=1}^{n} E_{ef} \ln(E_{ef}); (e = 1, 2, \ldots, n; f = 1, 2, \ldots, m) \tag{4}$$

Next, the differentiation coefficient Q_f is calculated based on the entropy of the f th indicator.

$$Q_{f=}1 - G_f; \quad (f = 1, 2, \ldots, m) \tag{5}$$

Next, the weights R_f of each indicator are calculated using the differentiation coefficient of the f th indicator.

$$R_f = \frac{Q_f}{\sum_{f=1}^{m} Q_f}; \quad (f = 1, 2, \ldots, m) \tag{6}$$

Finally, the comprehensive index S_e of each subsystem is calculated separately.

$$S_e = \sum_{f=1}^{n} R_f A_{ef}; \quad (e = 1, 2, 3) \tag{7}$$

2.4. Coupling coordination model translation

The concept of coupling degree C is used to reflect the degree of mutual influence between systems. It has been widely applied in various fields, such as geography [57–59], economics [60–63], and tourism [64–66]. Its value ranges from 0 to 1, where a value close to 1 indicates a stronger interrelationship between systems, while a value close to 0 indicates a weaker interrelationship. In the study of population, economy, and grain development in various cities and counties of Jilin Province and Jiangsu Province, a three-system coupling coordination model [67] can be constructed to analyze the coupling and coordination relationship among them.

When n = 3, assuming $maxS_e$ is S_3.

$$\mathrm{C} = \sqrt{\left[1 - \frac{\sqrt{(S_3 - S_1)^2} + \sqrt{(S_2 - S_1)^2} + \sqrt{(S_3 - S_2)^2}}{3}\right] \times \sqrt{\frac{S_1}{S_3} \times \frac{S_2}{S_3}}} \tag{8}$$

$$\mathrm{T} = \mathrm{a}S_1 + bS_2 + cS_3, \mathrm{a} + \mathrm{b} + \mathrm{c} = 1 \tag{9}$$

$$\mathrm{D} = \sqrt{CT} \tag{10}$$

The equation S_1 represents the comprehensive index of the population system, S_2 represents the comprehensive index of the economic system, S_3 represents the comprehensive index of the grain system. C denotes the coupling coordination degree of the population system, economic system, and grain system. T represents the level of coupling coordination development. a、 b、 and c are the importance coefficients of the indicators in the population system, economic system, and grain system, respectively. Considering that the population system, economic system, and grain system are equally important for the sustainable and healthy development of grain-producing provinces, we have $\mathrm{a} + \mathrm{b} + \mathrm{c} = 1$. By classifying the coupling coordination degree of the population system, economic system, and grain system, it becomes easier to directly reflect the degree of coupling coordination among the three systems. Based on existing literature research [45], the classification of the coupling coordination degree and coordination development degree of the population, economic, and grain systems are shown in Table 2, which reflects the system coupling coordination and coordination development situation.

Firstly, collect data; secondly, process the data using the entropy weight method (Formulas 1 to 7); then, substitute the processed data into the coupling coordination model formulas (Formulas 8 to 9); finally, obtain the coupling coordination degree (C) and coordination development degree (D).

3. Results and analysis

3.1. Analysis of the temporal and spatial evolution of population-economy-grain coupling coordination

Based on the aforementioned method, coupling coordination analysis was conducted on a total of 79 counties in Jilin Province and Jiangsu Province from 2000 to 2020. Specifically, the coupling degree values for the years 2000, 2005, 2010, 2015, and 2020 were extracted. These values were then processed using ArcGIS 10.8 for spatial visualization, resulting in the spatial distribution of population, economy, and grain coupling coordination in Jilin Province(Fig. 1) and Jiangsu Province(Fig. 2).

Table 2
Classification of coupling and coordinated levels.

Coupling Coordination Degree *C*	Level	Coordination Development Degree *D*	Level
0–0.19	Severe Imbalance	0–0.19	Severe Imbalance
0.2–0.39	Mild Imbalance	0.2–0.39	Mild Imbalance
0.4–0.59	Transitional Development	0.4–0.59	Transitional Development
0.6–0.79	Initial Coordination	0.6–0.79	Initial Coordination
0.8–1.00	High-Quality Coordination	0.8–1.00	High-Quality Coordination

From a temporal perspective, in the year 2000, the counties in Jilin Province that exhibited a high level of population, economy, and grain coupling coordination were primarily located in the northwestern region of Changchun City. Counties with severe imbalance were observed in Dehui City, Tumen City, and Longjing City. By 2005, there was a decline in the coupling coordination level in Jilin Province, and counties with severe imbalances were scattered along the province's border. Data analysis indicated that the decline in the economic system, particularly in the secondary industry value and industrial output value, significantly impacted the decrease in coupling coordination. Counties with high-quality coordination were dispersed throughout Jilin Province. By 2010, all counties in Jilin Province demonstrated high-quality coordination. In 2015, counties with high-quality coordination were dispersed within the region, while Fuyu City was in a transitional development stage, and other counties maintained a coordinated level of coupling coordination. By 2020, Tumen City, Tonghua City, Huinan County, Yitong County, Dongliao City, and Dongfeng County in Jilin Province were in a transitional development stage, while other counties had developed into a coordinated development stage. Data analysis revealed a continuous decline in the total population, a reduction in the labour force, stable economic development, and an expansion of grain production, which led to a decrease in the level of coupling coordination. High-quality coordination areas were mainly concentrated and contiguous in the northwestern part of Changchun City, while they were also dispersed in the eastern and southern regions of Jilin Province.

In Jiangsu Province in 2000, except for Guanyun County, Jinhu County, and Yizheng City, which were in a transitional development stage, the remaining counties were in a disordered state. Abundant labor force and a lower gender ratio played a significant role in the system. By 2005, counties with high-quality coordination in Jiangsu Province were concentrated in the southern part, while counties in the central region were in the initial coordination stage. Except for Pei County and Suining County in the north, which were in the initial stage of coordination, the rest of the counties were in a transitional development stage. By 2010, with the exception of Kunshan City and Zhangjiagang City, all counties in Jiangsu Province achieved high-quality coordination. By 2015, counties with high-quality coordination were dispersed along the borders of Jiangsu Province, while other counties were in the preliminary stage of coordination. The stable and increasing population, the growing labour force, the rising level of urbanization, the expanding economic growth, the decreasing land reclamation rate, and the increasing grain sowing area significantly impacted the coupling coordination level of these counties. As of 2020, only four counties in the southern and northern parts of Jiangsu Province were in a state of high-quality coordination, while the other counties were in the preliminary stage of coordination. Kunshan City became a "big city" [68] in 2022, and the increasing population and substantial economic growth had a significant positive impact on the population and economic systems of Kunshan City. However, the decrease in total grain production and land reclamation rate still had a negative impact on the comprehensive index of the grain system, significantly affecting the coupling coordination system.

From a spatial perspective, the population, economy, and grain coupling coordination in the western and central counties of Jilin Province have gradually surpassed those of Jiangsu Province after 2010. This can be attributed to Jilin Province's excellent grain production conditions, evolving industrial structure [69], and advantageous resource endowments, including fertile black soil and favorable water and thermal conditions [70]. In contrast, the eastern counties of Jilin Province, situated near the Changbai Mountains [71], focus more on developing forestry economies [72], resulting in relatively poor conditions for grain production. In Jiangsu Province, the coupling coordination in the southern and northern regions is relatively good. The northern region, located in the Huang-Huai Plain, is a crucial agricultural area in China with a flat terrain [73], high accessibility, abundant human resources [74], and a rational industrial structure. Consequently, the counties in both regions are in a state of high coordination. However, the southern region, closer to Zhejiang and Shanghai in the developed Yangtze River Delta, faces spatial competition from the well-developed economy. As a result, the southern counties of Jiangsu Province experience varying degrees of decline in land reclamation rates, grain sowing areas, and per capita grain production, placing them in the early stage of coordination.

Comparing Jilin Province and Jiangsu Province, the level of coupling coordination among county-level areas in Jiangsu Province is

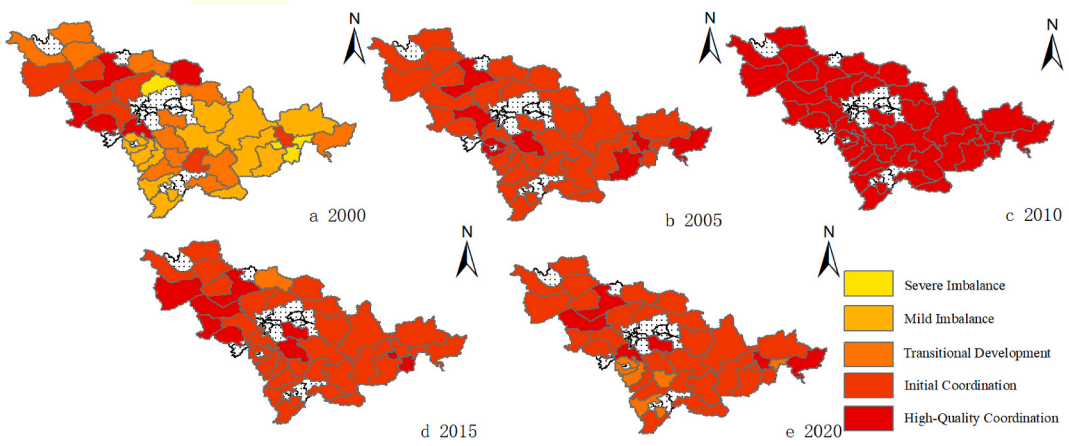

Fig. 1. Spatial distribution of population-economy-grain coupling coordination degree in Jilin Province from 2000 to 2020
Note: The production of the map was based on the standard map with the National Administration of Surveying, Mapping, and Geoinformation's approval number GS京(2022)106. The base map was used without any modifications.

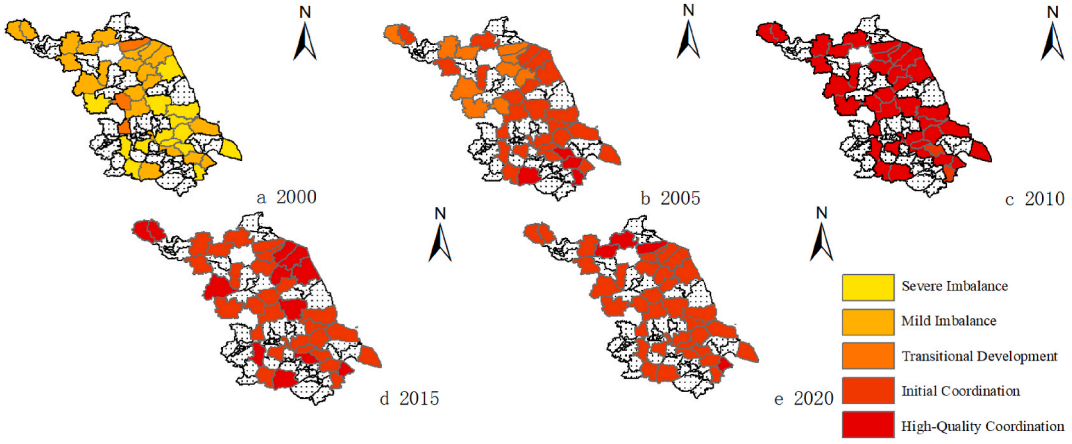

Fig. 2. Spatial distribution of population-economy-and grain coupling coordination degree in Jiangsu Province from 2000 to 2020. Note: The production of the map was based on the standard map with the National Administration of Surveying, Mapping, and Geoinformation's approval number GS京(2022)106. The base map was used without any modifications.

significantly more balanced than in Jilin Province. In Jilin Province, the counties in the northwest direction of Changchun City initially had lower levels of coupling coordination due to the strong "siphon effect" of Changchun City. However, as the economic level and population development of Changchun City stabilized, the surrounding counties, as major grain-producing areas, continuously expanded their grain production scale, boosting the surrounding counties' economic development. This led to a stable and increasingly high-quality level of coupling coordination. In Jiangsu Province, strong economic interdependence between cities and surrounding counties facilitates coordinated development. The population levels fluctuate to some extent, but the economic growth remains positive. The slight increase in grain production also contributes to the system's overall stability. It is worth noting that in 2015, both Jilin Province and Jiangsu Province experienced varying degrees of decline in coupling coordination. In Jilin Province, this was due to a slowdown in economic growth and continued negative population growth, which had a negative impact on the system. In Jiangsu Province, the stable population level and the difference between the growth rates of grain production and the economy negatively affected the coordination level. In Jilin Province, regional differences are evident in the eastern region's slow economic development and population growth. The total population in these counties continues to decline while GDP remains stable and per capita local government expenditure steadily increases. There is a disconnection between economic development and population levels, and the slow growth of grain sowing area and land reclamation rate contribute to the stagnation of coupling coordination in the eastern region of Jilin Province. However, the surrounding counties in the Changchun-Tumen area have shown good levels of coupling coordination in recent years, indicating closer connections among the population, economy, and grain systems. This is closely related to the regional geographic location, resource conditions, industrial structure, and transportation. In Jiangsu Province, the counties in the northern region of Su Bei have achieved simultaneous economic growth and increased grain production. The expansion of grain sowing area and grain output is in line with the economic level, ensuring a stable coordination level in the system. The cities in the Yangtze River Delta region exert a strong spillover effect on the surrounding counties in Jiangsu Province. With a large economic stock and rapid growth in incremental output, the population status in these countries has remained the same. However, the growth rate of the grain system is significantly disconnected from the economic system, which is a significant factor contributing to the large number of counties in Jiangsu Province being in the preliminary stage of coordination. The counties in the western region of Jilin Province, located near Liaoning Province, radiate from the capital city of Changchun, and the economic activities and population movement in the surrounding counties have become increasingly closely linked. In recent years, more emphasis has been placed on grain production, resulting in good development of the coupling coordination level in the three systems. For other counties and cities in Jilin Province, the level of coupling coordination has been continuously improving. On the one hand, they are negatively affected by the population outflow issue in Jilin Province, which impacts labour conditions. The increased per capita government expenditure and the small increase in GDP put significant pressure on the economic system. On the other hand, the mountainous areas in the eastern region of Jilin Province have a low land reclamation rate, which cannot have a significant positive impact on the coupling coordination system, leading to a slow progression in the level of coupling coordination.

3.2. Analysis of the spatiotemporal evolution of population, economy, and grain coordination development

Based on the determined research methodology and collected data, an analysis of the coordination development degree was conducted for a total of 79 county-level regions in Jilin Province and Jiangsu Province from 2000 to 2020. The data for the years 2000, 2005, 2010, 2015, and 2020 were selected, and spatial visualization processing was performed using ArcGIS 10.8 to depict the spatial distribution of the population, economy, and grain coordination development degree in Jilin Province(Fig. 3) and Jiangsu Province (Fig. 4) for each of the five years.

From a local perspective, in the year 2000, both Jilin Province and Jiangsu Province were in a state of imbalance in coordination

development. The underlying factors were influenced by the relatively low level of economic development in both provinces at that time. By 2005, there was an improvement in the coordination development level in both provinces. All county-level regions in Jilin Province were in a state of mild imbalance, while some county-level regions in Jiangsu Province were severely imbalanced due to slow economic growth. By 2010, there were significant regional differences in the coordination development degree among the county-level regions in Jilin Province. Some western and eastern county-level regions were in a state of imbalance. These imbalanced regions were constrained by lower coordination development level indices, indicating a high degree of coupling coordination and a low level of coordination development. At this time, Changchun, as the provincial capital, still exhibited strong suction effects and polarization, which affected the coordination development degree of the surrounding county-level regions. Jilin City demonstrated strong trickle-down effects, providing strong support to the surrounding county-level regions. In Jiangsu Province, the transitional development of county-level regions appeared scattered and gradually spread. The grain system in the northern part of the province continuously improved in grain production while the land cultivation rate decreased, leading to an improvement in the coordination development index. By 2015, the regional distribution of coordination development degrees in Jilin Province and Jiangsu Province showed similarities. The entire province gradually progressed to the transitional development stage. By 2020, the coordination development degree in Jilin Province's county-level regions followed a similar pattern to the coordination degree. Many county-level regions experienced a decline in coordination development degree. The slowdown in the growth rate of the secondary industry's value-added and industrial output and the decrease in the labour force population had a negative impact on the coordination development degree of county-level regions. In Jiangsu Province, the coordination development degree of all county-level regions entered the transitional development stage. The economic indicators continued to perform strongly, while the population system and grain system exhibited varying degrees of fluctuation.

From a holistic perspective, the overall development of population, economy, and food coordination in Jilin Province over the twenty-one years has remained in a state of imbalance and transitional development without widespread severe imbalance. This indicates that despite the challenges of negative population growth, outflow of labour force, economic decline, and black soil protection in Jilin Province, the overall development trend remains stable and manageable. There was a widespread and severe imbalance in Jiangsu Province in 2000, as influenced by the specific years chosen for analysis. However, in subsequent years, the level of coordinated development steadily improved, transitioning from scattered points to overall transitional development in all counties. Jiangsu Province also faces challenges such as population ageing, slowed population growth, and the conversion of agricultural land for construction purposes. However, the overall development trend remains stable and positive. However, upon closer examination of the individual systems, the population and economic indicators in the northern region of Jiangsu Province are relatively poor. The steady development of food indicators has driven the overall coordination of the system. In the southern region of Jiangsu Province, the food indicators are relatively poor, but the increase in the labour force and the rise in total exports have become critical factors in stabilizing the system.

4. Conclusion

4.1. The impact of the population system on coupling coordination level

Observing the characteristics and trends in coupling coordination and coordination development degree of population, economy, and grain in counties of Jilin Province and Jiangsu Province, the two major grain-producing areas, it is evident that since the beginning of the new century, the relationship among these three aspects has gradually deepened, moving towards a high level of coupling coordination. Throughout the research period, indicators related to the population system in both Jilin Province and Jiangsu Province

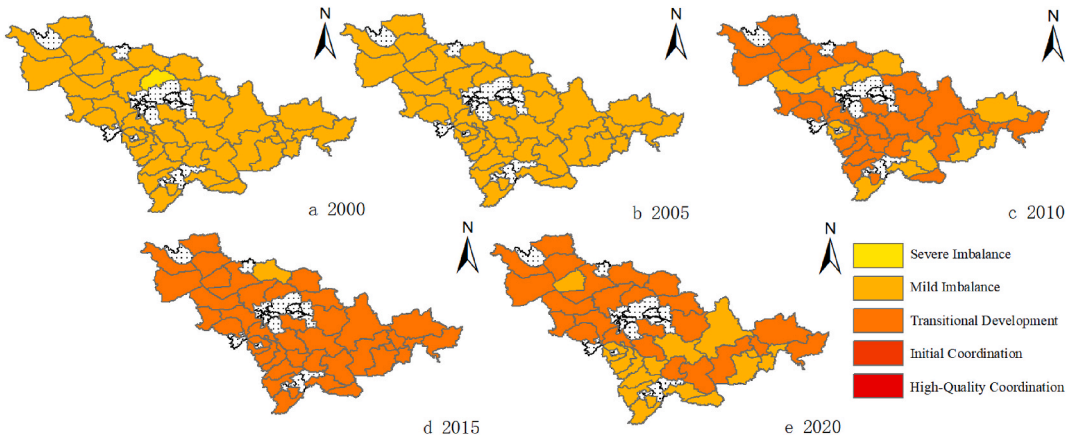

Fig. 3. Spatial distribution of coordinated development degree of population, economy and grain in Jilin Province from 2000 to 2020
Note: The production of the map was based on the standard map with the National Administration of Surveying, Mapping, and Geoinformation's approval number GS京(2022)106. The base map was used without any modifications.

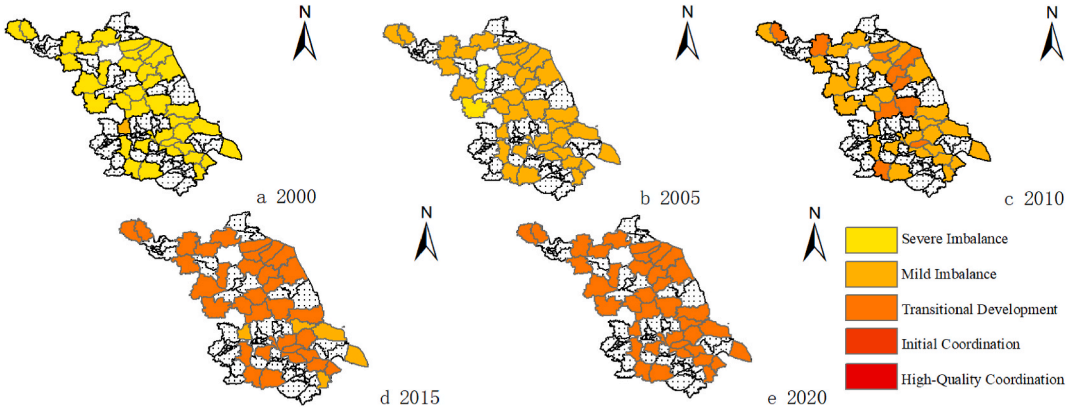

Fig. 4. Spatial distribution of population, economy and grain coordinated development degree in Jiangsu Province from 2000 to 2020
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have exhibited overall stability. In Jilin Province, influenced by natural conditions and economic development levels, there is a discernible decline in population across various counties, and the consequent population outflow negatively impacts the coupling coordination system. The decline in population density and labor force, attributable to the total population, provides insufficient positive support for the system's development. Indicators such as population gender ratio, urbanization level, technical personnel in healthcare institutions, and total hospital beds reflect that the improvement of economic levels has a positive impact on the quality of the population, thereby influencing the quality of coupling coordination in a positive manner. In the case of Jiangsu Province, with its geographical advantages and higher economic development levels, it attracts an increasing number of local and external populations due to its advantageous location factors. The continuous increase in population, population density, and labor force contributes to the demographic dividend for industrial development in Jiangsu Province, positively impacting the coupling coordination levels of the three systems. Moreover, the levels of urbanization, technical personnel in healthcare institutions, and total hospital beds are steadily increasing year by year. The good economic foundation and the aforementioned factors mutually promote each other, positively contributing to both coupling coordination and coordination development degree.

4.2. The impact of the economic system on the level of coupling coordination

Since 2000, China's economy has undergone rapid development; however, economic conditions vary among different regions. Jilin Province and Jiangsu Province, both major grain-producing regions in China, exhibit significant disparities in their economic levels. While Jilin Province's county-level GDP has experienced a gradual deceleration in growth after a period of high-speed expansion, local fiscal expenditures have consistently widened. Some counties heavily rely on transfer payments, leading to adverse effects on the economic system. Even in major grain-producing counties of Jilin Province, the primary industry's scale is relatively modest and fails to effectively stimulate local economic development. Geographically distant counties, situated in grassland or mountainous areas, face economic challenges with weak foundations, lacking pivotal industries, and showing slow progress in the secondary industry. Consequently, industrial output value and total exports are limited, and there is a weak economic linkage with surrounding regions, negatively impacting the coupling coordination level and coordinated development degree of the three systems.

After a phase of rapid expansion, the secondary industry and industrial development in Jilin Province have transitioned into a stable period, lacking new economic growth points, but overall contributing positively to the coupling coordination level and coordinated development degree. In Jiangsu Province, with a favorable economic development status, county-level industries interact and coordinate effectively with those in the province and surrounding areas. However, the relatively small scale of the primary industry negatively affects the economic system.

4.3. The impact of the grain system on the level of coupling coordination

Jilin Province is located in one of the world's three major black soil areas, with superior soil conditions and flat terrain, making it a crucial region for grain production in China. At the spatial scale, counties with a high level of coordination in coupling are primarily major grain-producing counties with abundant land resources. These counties show an annual increase in grain production, per capita grain production, land reclamation rate, and grain sowing area, accompanied by a gradual decrease in the use of pesticides per unit of cultivated land. This reflects that major grain-producing counties, while emphasizing grain production, can also balance population and economic considerations, and pay attention to the protection of black soil. Regions with fluctuating coupling coordination are mainly distributed in economically weaker grain-producing counties. In 2010, most counties in Jilin Province were in a state of high coordination, but by 2020, the number of counties in this category had significantly decreased. Regions with advantages in grain production have more favorable geographical conditions, and while maintaining an increase in grain production, they also gradually

strengthen the coupling coordination with population and economy. Jiangsu Province is located in the middle and lower reaches of the Yangtze River, with flat terrain and favorable hydrothermal conditions, making it a traditional grain-producing region in China. The superior geographical location also provides a good foundation for the development of industry and services. In the economically developed southern part of Jiangsu Province, there is a serious decline in grain production, while the northern region maintains stable growth in grain production. In terms of coordination development, most counties in Jilin Province were in the best state in 2015, in a stage of excessive development, but by 2020, coordination development showed negative growth, and some counties were in a state of mild imbalance. This trend aligns with the changes in coupling coordination in the local area. Benefiting from a strong economy, Jiangsu Province generally maintains good coordination development, even if some counties experience negative population growth, a decrease in grain production, and a decline in land reclamation rate. While maintaining the development of economic production, the coordination development of counties in Jiangsu Province still maintains a positive trend.

5. Discussion

Several measures can be taken to promote the coordinated development of the economy, population, and grain production in grain-producing counties. Firstly, it is crucial to continue supporting the development of areas with good coordination. Changes in coupling coordination within provinces often radiate from central cities to surrounding areas. In areas with good coordination, efforts should be made to support underdeveloped regions, focusing on promoting balanced industrial development and high-quality development of the primary industry. It is crucial to determine the development types and positioning of industries in each county, align national functional zoning requirements with local conditions, and select industries suitable for each specific area. Emphasis should be placed on the development of key counties and nodes, with a focus on transferring heavy industries and emerging industries with strong agglomeration effects to surrounding counties and cities to enhance the radiation effect of node counties. Secondly, traditional grain-producing countries face challenges such as industrial upgrading, depletion of conventional resources, and lower transportation convenience. Therefore, emphasis should be placed on industrial transformation to avoid the economic decline caused by the "resource curse," and efforts should be made to develop modern agriculture. County towns should fully act as urban centers and provide more employment opportunities. In the face of population outflows and limited government financial resources, traditional advantages in agricultural production should be leveraged to develop local agricultural processing industries and agricultural production services. Efforts should be made to create brands for agricultural products related to animal husbandry and promote the development of new industries and potential industries, gradually transforming the traditional investment-driven economic growth model in economically backward areas, eliminating outdated production capacity, and creating new driving engines for economic growth. Furthermore, greater attention should be given to grain production, increasing investment in grain production, further expanding the grain sowing area, and increasing grain production. Building on the advantages of a strong economic foundation, efforts should be made to promote the development of the grain-producing regions, establishing a cycle of benefits and ensuring food production.

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Additional information

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Declaration of competing interest

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