The Evolution Characteristics and Planning Regulation of the Population-cultivated land-food (PCF) system in Rural Counties of China

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Abstract
Industrialization and urbanization have profoundly transformed China's county-level population structures, land-use patterns, and food production systems. Variations in natural conditions and urbanization levels have resulted in uneven spatial distributions of population, cultivated land, and food production. Exploring the dynamic evolution of this system in China's counties and formulating targeted planning and regulatory strategies hold significant theoretical and practical value. This study aimed to reveal the internal dynamics of the PCF system through an analysis of its evolution across 1,848 county-level units (excluding urban areas) during 2000, 2010, and 2020. After evaluating system coordination and classifying rural areas into distinct types based on coupling modes though an indicator system, the study proposed targeted planning and regulation strategies for counties with differing coupling modes, emphasizing system coordination.

Keywords: Food Security; Population-Cultivated Land-Food System (PCF System); Urbanization and Rural Development; Planning Strategies

1. Introduction

Food security is related to the national economy, people's livelihood and sustainable development, and is a necessary guarantee for China's modernization. The population-cultivated land-food (PCF) system is a complex system based on the development and utilization of arable land resources within a certain geographical area, with food production, consumption and circulation as the central links, and the ultimate goal of meeting human food needs (Bao and Fang, 2007). As a bridge connecting cities and villages, the dynamic evolution of the population, cultivated land and food system in the county is not only related to the sustainable development of the rural economy, but also directly affects the country's food security and the stable development of society. Therefore, it is of great theoretical value and practical significance to deeply study the evolution characteristics of the rural population - farmland - food system in China's counties and explore the corresponding planning and regulation strategies.

With the continuous development of industrialization and urbanization in China, the population structure, land use and grain production patterns of counties and villages have undergone profound changes. Overall, due to different natural conditions and urbanization levels, the regional distribution of population, cultivated land and grain production in China is uneven. The per capita cultivated land generally shows a distribution characteristic of less in the east and more in the west (Ge, Long and Yang, 2018), and the per capita grain output also shows a characteristic of more in the central and western regions and less in the east. The national grain output and cultivated land area are mainly concentrated in the middle and low-level economic development areas (Wang et al., 2024). Different regions are facing pressure on cultivated land and grain production due to differences in population demand. Rapid urbanization has caused China's rural population to continue to move to cities, resulting in a shortage of rural labor and more unbalanced regional development, which has had a certain impact on agricultural production and food supply (Mu and Lin, 2020). At the same time, the reduction of rural cultivated land resources and the intensification of the "non-grain" and "non-agricultural" trends have also challenged the stability and sustainability of grain production (Zhang et al., 2023). On the one hand, county villages are still an important space for China to carry out grain production functions and rural labor. How to ensure food security and coordinate the relationship between population , cultivated land and food systems? On the other hand, villages in different regions are affected differently by the evolution of urban-rural relations, forming different

development opportunities and conditions (Zhang and Sun, 2019). How to combine past research on rural classification development with the characteristics of county rural economic and social development to carry out more targeted classification planning and regulation of villages has become an urgent problem to be solved.

2. Theoretical basis

This study aimed to reveal the internal laws and dynamic mechanisms of the population-cultivated land-food (PCF) system in Chinese counties and villages through the analysis of its evolutionary characteristics, and to provide corresponding planning, regulation and guidance for rural types with different systemic coordination characteristics. In the semi-open population-cultivated land-food complex system, the cultivated land area and its cultivated land planting structure, grain planting area and multiple cropping index in different regions affect the efficiency of cultivated land, thus determining the grain output. Grain output and the number of permanent residents determine the per capita grain possession. Regions where the per capita grain possession is greater than the per capita grain demand become the main grain production areas, dividing the pattern of grain input and output. The cultivated land area and the number of rural population determine the per capita cultivated land area, reflecting the possibility of large-scale production of cultivated land in the region. In the process of urbanization, the population continues to move and the land use type continues to transform, resulting in the continuous changes in the county's permanent population, rural population and cultivated land area, which are the main driving forces for the dynamic evolution of the population-cultivated land-food system, as shown in Figure 1.

Based on this system, the article firstly sorted out the evolution process of county rural population-cultivated land-food system, and analysed the main factors affecting their evolution. Then the main indicators reflecting the coordination of the PCF system, such as per capita cultivated land area and per land grain output, were adopted to analyse the change coupling model in rural areas of counties across the country. Based on the differences in the types of change coupling patterns, targeted planning and regulation strategies were proposed to provide theoretical support and practical guidance for the sustainable development of county rural economy and national cultivated land and food security.

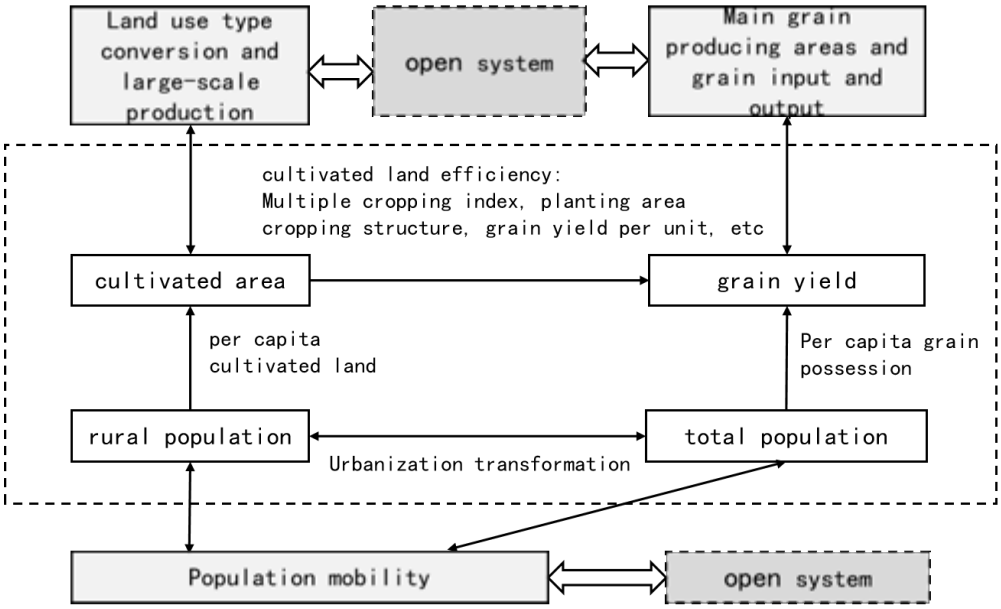


Figure 1 Population-arable land-food system operation mechanism diagram

3. Research Methods

3.1. Study area

The research object consisted of 1,848 county-level units. This study was based on the administrative divisions of 2020, integrating counties and county-level cities. Four prefecture-level cities without county-level administrative regions (Dongguan City and Zhongshan City in Guangdong Province, Danzhou City in Hainan Province, Jiayuguan City in Gansu Province), as well as the Hong Kong Special Administrative Region, the Macao Special Administrative Region, and Taiwan,were were excluded. In addition, due to the missing values of individual variables in some administrative units, the number of samples finally included in the research analysis was 1,848 .

3.2. Data sources

The county-level administrative unit vector data used in this study came from the Third National Land Survey database in 2020. Population data came from county-level demographic statistics from the Fifth (2000), Sixth (2010), and Seventh (2020) National Population Censuses. Cultivated area data came from the cultivated land area of "*China Agricultural Statistical Yearbook*" *(2001)*, the 2010 data of the Second National Land Survey data (https://gtdc.mnr.gov.cn/Share?UiNMsBTfPrya=1712637735952#/secondSurvey) verified with the China Annual Cultivated Land Dataset (CACD) (https://doi.org/10.5281/zenodo.7936885) released by Dr. Tu Ying in Professor Gong Peng's team at Tsinghua University with a resolution of 30m×30m, and the 2020 data of the Third National Land Survey data (https://gtdc.mnr.gov.cn/Share#/thirdSurvey). The grain production data for 2000 and 2010 were derived from the "*China County Statistical Yearbook*" *(2001, 2011)*, and the grain production data for 2020 were derived from the statistical yearbooks and the statistical bulletin on national economic and social development of various provinces and cities .

3.3. Research methods

3.3.1. Standard deviation ellipse

The standard deviation ellipse is a spatial statistical method widely used to describe the spatial distribution characteristics of geographical elements, and it depicts the spatial morphological characteristics of geographical elements such as centrality, spread, and directionality. This study constructed standard deviation ellipses of rural population, cultivated land area, and grain output in counties across the country from 2000 to 2010 and from 2010 to 2020, to analyze the spatial-temporal evolution of rural population, cultivated land area, and grain output.

3.3.2. Variation of coupled mode measurement

This study measured the changing coupling pattern of rural PCF system elements based on the change rate of per capita cultivated land area and per-acre grain output in counties across the country from 2000 to 2010, 2010 to 2020 , and 2000 to 2020.

$$GRit=(Git-Gi0)/Gi0$$

$$LRit=(Lit-Li0)/Li0$$

Where: i represented the county; GRit and LRit represented the change rates of per capita cultivated land area and per-land grain output in county i in year t respectively; Gi0 and Git represented per capita cultivated land area in county i in the base year and year t; Li0 and Lit represented per-land grain output in county i in the base year and year t.

Four coupling types could be divided according to the different changes of per capita cultivated land area and per-land grain output in different stages:

- If GRit>0 and LRit>0, the per capita cultivated land area and per-land grain output of the county were in the "same increase" mode.
- If GRit>0 and LRit<0, the per capita cultivated land area of the county increased and the per-land grain output decreased.
- If GRit<0 and LRit>0, the per capita cultivated land area of the county decreased and the per-land grain output

increased.

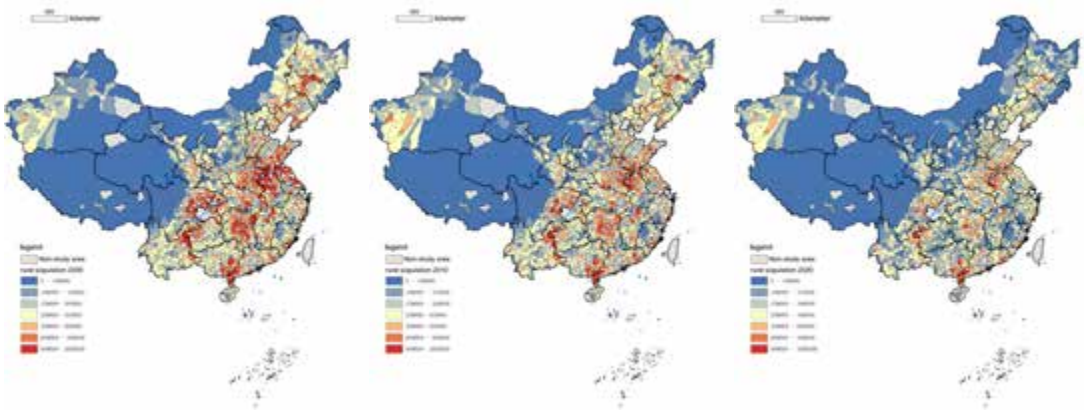
• If GRit<0 and LRit<0, the per capita cultivated land area and per-land grain output of the county were in the "same decrease" mode.

4. Analysis on the spatial-temporal evolution of PCF system in counties

4.1 . Dynamic changes in the total amount

4.1.1. Dynamic characteristics of rural population in counties

In the two decades since 2000, the number of rural populations in all regions of the country has shown a straight-line downward trend. The total rural population has decreased from 6.092×10^{8} to 3.8046×10^{8}, a decrease of 62.45% of the original. Among them, the rural population reduction rate in the central region and the northeast region were relatively high, at 42% and 39% respectively, while the rural population reduction rate in the western and eastern regions was about 34%. From 2000 to 2020, China's urbanization has made great progress, and the central-western regions have become the largest rural population transfer and outflow areas, with significantly decreased rural population. However, due to the geographical location of the western region being farther away from the main inflow areas of the eastern population, the industrial model was more backward, and the rural population base was large. After population mobility, it was still the region with the largest rural population. In addition to being affected by urbanization, the reduction of rural population in the northeast region was also related to the large-scale mechanization transformation of agricultural production. The eastern region was mainly undergoing its own urbanization process, and most of the rural population was converted into urban population on the spot, and the number of rural population continued to decline. While the total population of the country was increasing, the large-scale reduction of rural population has brought challenges to food production.



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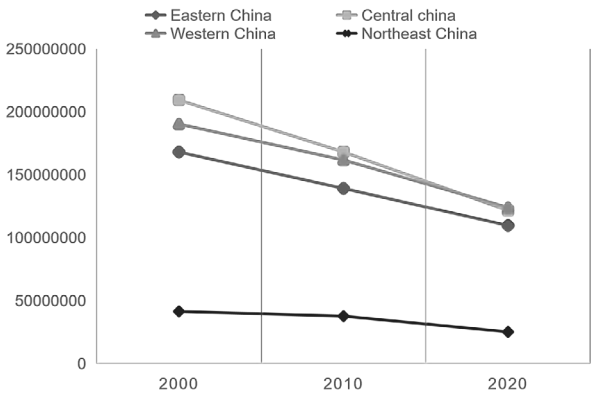
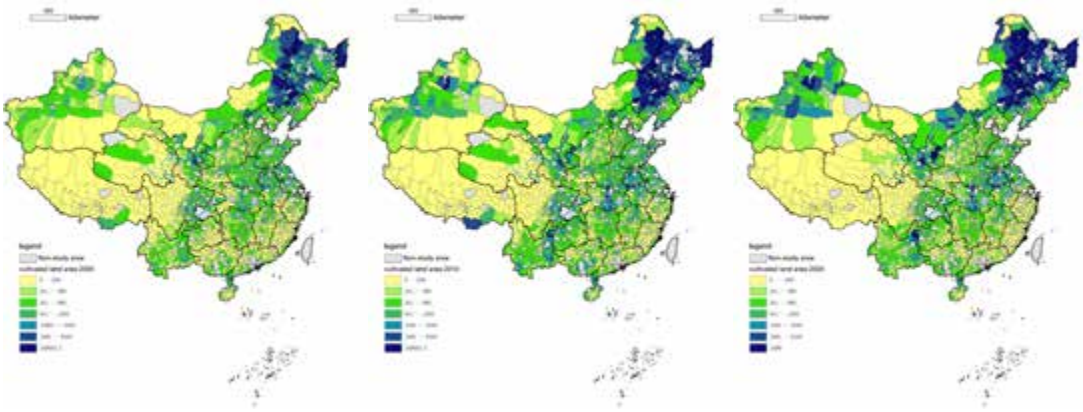


Figure 2 The spatiotemporal evolution of rural population

4.1.2. Dynamic characteristics of cultivated land in counties

The changes in cultivated land area in counties in different regions of the country were quite different. Except for the eastern region, the cultivated land area in counties in other regions has increased. Among them, the western region and the northeastern region have shown a continuous growth trend, which was related to the low urbanization level in the western region and the fact that agricultural planting was still the main industry. Affected by the profound impact of the project of returning farmland to forest and grassland since the development of the western region, the growth rate of cultivated land area in the western region has gradually slowed down. Thanks to the good natural farming conditions, the northeastern region has become the most important grain production base in China. With the continuous increase of China's population, the demand for grain has also increased accordingly, and the cultivated land area in the main grain-producing areas of the northeast has increased significantly. The cultivated land area in the central region first increased and then decreased, which was related to the adjustment of the industrial structure in the region and the rapid development of urbanization occupying a large amount of cultivated land. The eastern region has a dense population and a high level of urbanization. The continuous agglomeration of population has generated a greater demand for construction land. At the same time, the rapid economic development has continuously increased the value of land, transformed land use, and continuously reduced the cultivated land area. Although the cultivated land area in the country has increased slightly overall, the distribution of cultivated land has become more unbalanced.



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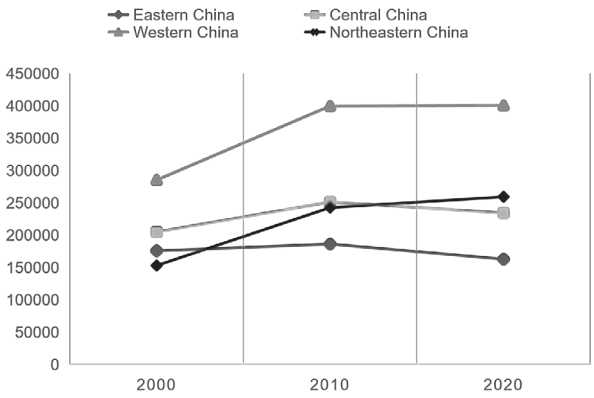
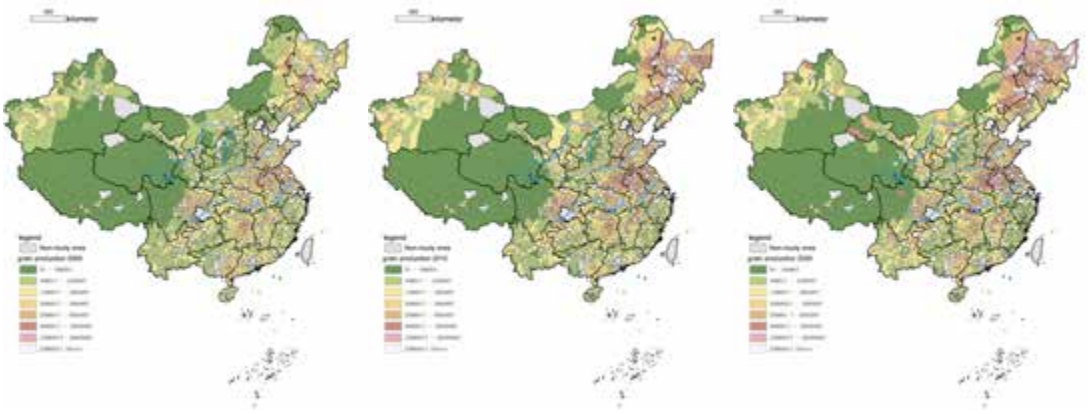


Figure 3 Spatial and temporal evolution of cultivated land area

4.1.3. Dynamic characteristics of grain output in counties

The national grain output showed an overall growth trend between 2000 and 2020 (Figure 4). Due to the rapid development of urbanization and the adjustment of industrial structure, the eastern region has insufficient potential for growth in grain output, while the grain output in other regions has increased significantly. The

large-scale increase in grain output under the condition of no significant increase in the overall cultivated land area showed that China had improved the multiple cropping index and grain farming technology level, and the average grain output per land had increased. It was also affected by relevant agricultural benefit policies, and farmers' enthusiasm for growing grain has increased. After 2010, the increase in grain in various regions slowed down simultaneously, which was greatly affected by the change in farming structure. With the development of the economy and the improvement of people's living standards, people's demand for agricultural products has become more diverse, and the development trend of "non-agriculturalization" and "non-grainization" was obvious. It could be seen that both market factors and national policies had a great impact on grain production, and reasonable macro-control by the state was needed to ensure the stability of grain production.



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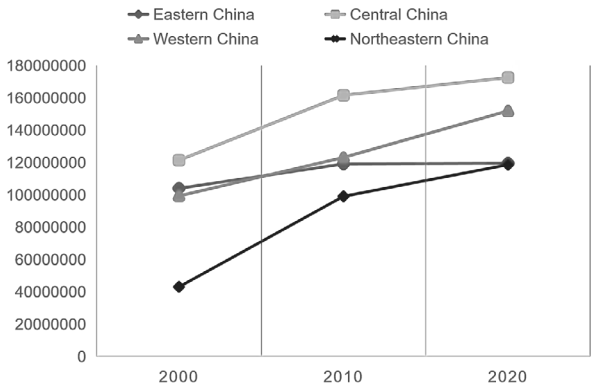
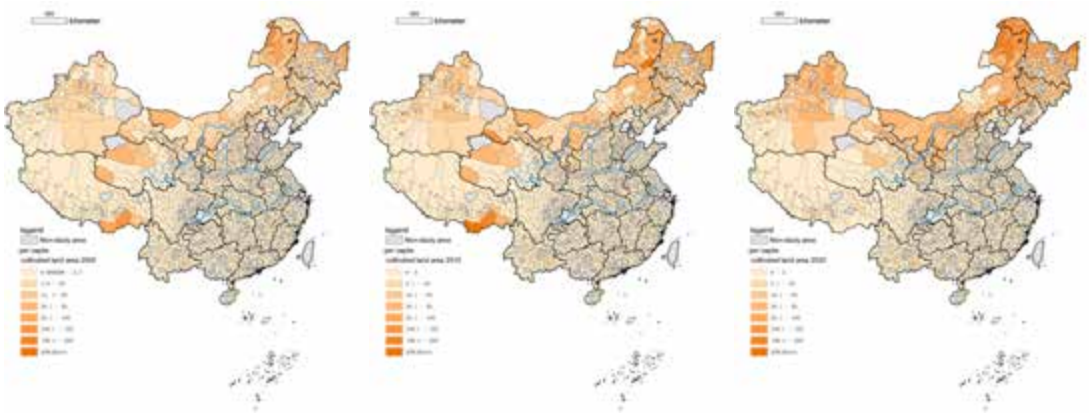


Figure 4 Spatial and temporal evolution of grain production

4.2 . Dynamic changes in per capita/unit amount

4.2.1. Changes in per capita cultivated land area

The per capita arable land area of the rural population in counties has increased overall, with the average value increasing from 2.78 mu in 2000 to 6.79 mu in 2020, which was related to the large-scale loss of rural population in the process of urbanization. The center of gravity of per capita arable land area continued to move to the northeast. The northern part of the Northeast, central Inner Mongolia, and the eastern part have vast land and sparse population, good farming conditions, and have always been areas with large per capita arable land area. While Central China, East China, and South China were densely populated, with a high level of urbanization, and arable land was facing great pressure. There was a spatial dislocation between areas with abundant per capita arable land and areas with concentrated populations and developed economies in China.



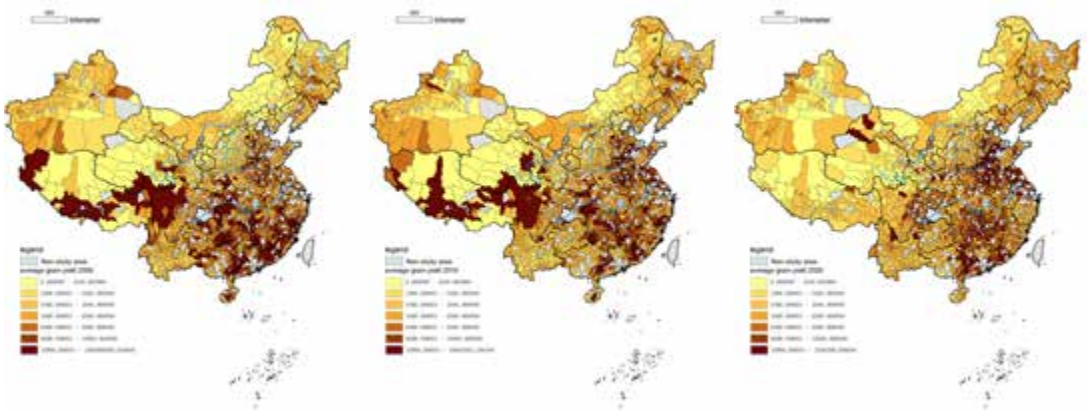
(a)2000 (b)2010 (c)2020

(d)standard deviation ellipse of per captia cultivated land area

Figure 5 The spatiotemporal evolution of per capita cultivated land area

4.2.2. Changes in grain output per county area

The per capita grain output in counties across the country varied greatly. With the same area of arable land, the grain yield per unit area in the eastern regions such as East China and South China and the middle reaches of the Yangtze River in the central region was relatively high, which was the focus of per capita grain output in China. This was related to the suitable climate and topographic conditions in these regions, the high grain multiple cropping index, the long history of farming, the good economic development, and the advanced agricultural technology. As an important grain export base, the Northeast region had a large total grain output, but due to the cold climate conditions and the vast area of arable land, the per capita grain output was not as good as that in the eastern region. Since different regions had different production characteristics, we should further improve the level of planting technology and increase the per capita grain output so as to ensure food security.



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(d)standard deviation ellipse of average grain yield

Figure 6 Spatial and temporal evolution of average grain yield

5. Classification of coupling patterns of PCF system in counties

In the complex system of population-cultivated land-food, population and cultivated land are more important factors of change. The per capita food output and demand in different regions are different, but they can be regulated and redistributed through market operations and national policies. The per capita arable land area of rural population and per-land food output more accurately reflect the development potential and production level of regional food production from the perspectives of "who will cultivate the land", "how much land there is", and "how efficient the cultivated land is", which is related to the national food production security. Therefore, the following focused on analyzing the coupling types of per capita arable land area and per-land food output in counties in different regions across the country, and provided feasible strategic suggestions for the development of food security in the process of new urbanization.

Based on the measurement of the coupling pattern of changes in per capita cultivated land area and per-land grain output in counties across the country, four classifications were produced: the "simultaneous increase" pattern; the "reduction in population, reduction in land, and increase in grain" pattern; the pattern in which per capita cultivated land area in rural areas increased and per-land grain output decreased; and the "simultaneous decrease" pattern.

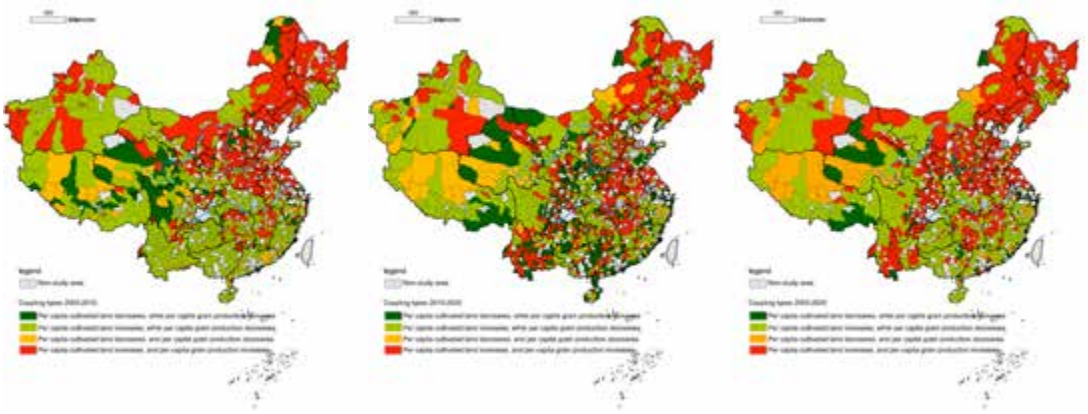
The first is the "simultaneous increase" model of increasing per capita cultivated land area and per-acre grain output in rural areas. From 2010 to 2020, this type of county units accounted for about 38.1% of the total, mainly

concentrated in Northeast China, North China, Jianghuai region, eastern Inner Mongolia, northern Shaanxi, Hunan and parts of Jiangxi Province. These areas were relatively traditional agricultural areas with good natural conditions and a long history of grain farming, and still maintained a certain growth rate of cultivated land area. At the same time, in the process of local urbanization and population flow to neighboring developed eastern regions, the local rural population has continued to decline, resulting in a continuous expansion of per capita cultivated land in rural areas. The advancement of agricultural technology and the use of mechanized production have led to a rapid increase in grain output and a simultaneous increase in per-acre grain output. This type of county should seize the advantages of grain production, make full use of natural conditions, further promote large-scale mechanized grain production, and assume the role of the main force in ensuring national food security and food supply.

The second is the "reduced population, reduced land, and increased grain" model, where the per capita cultivated land area in rural areas decreased and the per-land grain output increased. From 2010 to 2020, this type of county units accounted for about 22.4% of the total, mainly distributed in the middle and upper reaches of the Yellow River and the southwestern regions of Yunnan, Guizhou, Sichuan, and Guangxi. These areas were mainly Gobi deserts and mountains. Desertification and rocky desertification have greatly affected grain planting. In the process of ecological and environmental protection in China in recent years, many low-quality cultivated lands in these areas have been reasonably retired, and the cultivated land area has continued to decrease. Under the condition of generally improved grain planting technology, the per-land grain output has increased. At the same time, due to problems such as transportation and terrain, these areas have lagged behind in social and economic development. There were still a large number of rural population engaged in the primary industry. The speed of land retirement was faster than the speed of rural population loss, and the per capita cultivated land area in rural areas showed a downward trend. This type of county should promote the coordinated development of urbanization and ecological and environmental protection, increase investment in agricultural science and technology, continuously improve the efficiency of cultivated land, and achieve green and efficient development.

The third is the pattern of increasing per capita cultivated land area in rural areas and decreasing per-land grain output. From 2010 to 2020, this type of county unit accounted for about 34.5% of the total, mainly distributed in Northwest Sichuan, Xinjiang and most areas of the southeastern coastal areas. Northwest Sichuan and Xinjiang have turned to the planting and processing of specialty agricultural products in recent years because the ecological environment was not suitable for grain production. While the cultivated land area has increased, the grain output has decreased. In addition, the rapid loss of rural population has led to an increase in per capita cultivated land area in rural areas, but a decrease in per-land grain output. Due to the rapid speed and high level of urbanization in the southeastern coastal areas, while the cultivated land has been transformed into other types of land use and the grain planting area has been reduced , the transformation of rural population into citizens has been more rapid, resulting in an increase in per capita cultivated land area and a decrease in per-land grain output under the condition that the rural population, cultivated land and grain output have decreased in the same direction. Regions with this pattern should vigorously develop intensive agriculture and invest more labor, capital and technical support in limited cultivated land areas.

Fourthly, the "simultaneous reduction" type, where the per capita cultivated land area in rural areas decreases and the per-acre grain output also decreases. This type of county unit had the least number of units, accounting for about 5% of the total from 2010 to 2020, and was scattered in the northeastern part of Zhejiang Province, the southeastern part of Fujian Province, and parts of northern Tibet. These areas were also facing a triple reduction in rural population, cultivated land area and grain output, but due to the rapid urban construction and industrial transformation in recent years, the reduction in cultivated land area and grain output was more obvious. Regions with this model should further optimize the planting structure and increase the grain self-sufficiency rate.



(a)2000-2010 (b)2010-2020 (c)2000-2020

Figure 7 Spatial distribution of coupling types of per capita cultivated land area and per-acre grain output in China

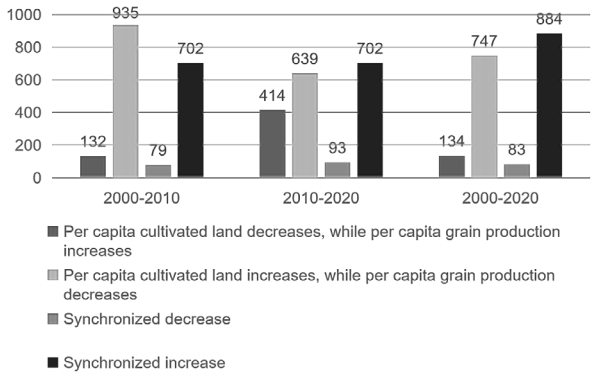


Figure 8 Distribution of coupling types between per capita cultivated land area and per-acre grain output in China

The characteristics and distribution types of the four modes can be summarized as shown in the following table:

Figure 9. Characteristics of coupling types between per capita cultivated land area and per-acre grain output in China

Dynamics of per capita cultivated land area	+	-	+	-
Dynamics of grain output per land area	+	+	-	-
Quantity ratio	38.1%	22.4%	34.5%	5.0%

Distribution	Northeast China, North China, Jianghuai region, eastern Inner Mongolia, northern Shaanxi, Sichuan, Hunan, and parts of Jiangxi Province	Middle and upper reaches of the Yellow River , Sichuan, Yunnan , Guizhou, Guangxi and other regions	Northwest Sichuan, Xinjiang and other areas; Most areas along the southeast coast	Yangtze River Delta and southeast coastal areas
Characteristics and causes	Good natural conditions and a long history of farming made it suitable for large-scale mechanized grain production.	The primary industry was still the main industry, and a large number of rural populations developed agriculture.	The ecological environment was not suitable for food production, so it is advised to turn to the cultivation and breeding of special agricultural products with the decreasing rural population.	The economy was relatively developed, the proportion of cash crops in the planting structure had increased, and the industry has transformed and developed.

Annotations: "+" is for "increase"; "-" is for "decrease".

6. Discussion and conclusion

6.1. Discussion

This study analyzed the dynamic change process and system coordination type of the population-cultivated land-food system in the rural counties of China from the perspective of "spatiotemporal evolution-change coupling-classification regulation", providing a reference for promoting the sustainable development of the rural economy in the counties and the national farmland and food security. Rural areas have important agricultural production functions and ecological product values. In the semi-open complex system of population-cultivated land-food in rural areas, the interaction between various elements promotes agricultural production progress and the balance of food supply and demand, and maintains the dynamic and coordinated evolution of the system, which is of great significance for ensuring national farmland and food security. This study analyzed the dynamic evolution characteristics and change coupling types of the rural population-cultivated land-food system in the rural counties of China, comprehensively considered factors such as natural geographical conditions, resource endowment differences, and county main functions, and proposed differentiated planning strategies for rural areas in counties with different change coupling modes from the perspective of population-cultivated land-food system coordination, including:

(1) The counties, with per capita cultivated land area and per capita grain output in rural areas increasing simultaneously, covered the main grain-producing areas and traditional agricultural areas in China, and were important responsibility areas for ensuring the country's cultivated land and food security. First of all, it is advised to base on the excellent natural resource endowment, strictly adhere to the red line of cultivated land, strictly implement the cultivated land protection system, strengthen soil protection and improvement, so as to achieve the dual guarantee of the quantity and quality of cultivated land resources, and ensure the sustainable

development of grain production. The outflow of rural population and urbanization provide possibilities for large-scale agricultural production. State-owned farms in some areas have the foundation for developing large-scale and mechanized grain production. By strengthening the introduction of agricultural talents and agricultural technology training, the capacity and efficiency of grain production can be enhanced, with the planting structure and grain production structure optimized to cultivate high-quality commercial grain varieties, thereby improving the quality and market competitiveness of grains. At the same time, in response to the trend of rural population decline, efforts should be made to promote the transformation of identity farmers into professional ones, strengthen the introduction and training of agricultural technical labor, improve the professional quality and skills of agricultural practitioners, ensure the supply and stability of technical agricultural labor, and better adapt to the situation of grain production.

(2) For counties where the per capita cultivated land area in rural areas has decreased and the per capita grain output has increased, the contradiction between agricultural resource utilization and the fragile ecological environment is the fundamental factor affecting the high-quality development of agriculture, and it also brings the dual pressure of cultivated land protection and ecological security. Therefore, it is of great importance to solve the problem of coordination between food security and ecological protection, reduce the loss of cultivated land and the destruction of the natural environment, attach importance to the ecological value of cultivated land, and implement the “three-in-one” cultivated land protection strategy of quantity, quality and ecology in the face of rigid resource constraints, so as to promote the sustainable utilization of cultivated land resources and high and stable grain yields. Relying on the long-term traditional agricultural foundation and relatively intensive agricultural labor resources, efforts should be made to improve agricultural technology and farmers’ skills through training and skills support, and improve the efficiency and quality of grain production. In combination with natural geographical characteristics and natural resource endowments, it is advised to optimize the planting structure and adjust the breeding methods according to local conditions, and improve the comprehensive benefits of agricultural production through the development of characteristic agriculture and ecological agriculture, so as to achieve system coordination and economic, social and ecological win-win results.

(3) In counties where the per capita cultivated land area in rural areas has increased and the per capita grain output has decreased, the long-term rapid urbanization of the population has led to a tense relationship between people and land in rural areas, and the trend of cultivated land becoming non-grain is obvious. Therefore, on the basis of keeping the red line of cultivated land to curb resource loss, attention should be paid to the decline in grain output caused by factors such as the loss of agricultural labor and natural conditions. Economically developed regions with special resources are encouraged to adjust appropriate agricultural planting structures, make full use of precious cultivated land resources, develop diversified and efficient characteristic rural industries and intensive agriculture, and optimize the industrial structure in rural areas. It is suggested that through measures such as policy support, industrial assistance, and agricultural services, a better entrepreneurial environment and development opportunities should be provided. Agricultural infrastructure should be strengthened, rural infrastructure and public services improved, and the quality of life and social environment in rural areas enhanced. This will attract urbanized population to return to their hometowns for employment and entrepreneurship, thereby revitalizing rural areas. Meanwhile, other suggestions include actively integrating into the national unified market, promoting the complementary development of grain crops and cash crops, in order to achieve stable cultivated land and sustainable agricultural development.

(4) Counties where the per capita cultivated land area and per-acre grain output decreased simultaneously are mainly in areas with relatively mature urbanization. The primary industry is no longer the main industry in the region, and cultivated land was constantly replaced by other land use types in the process of urbanization. Therefore, in response to the reality of the increasing pressure on cultivated land resources, it is urgent to optimize the allocation of land resources, avoid excessive occupation and destruction of cultivated land resources, further curb the reduction of cultivated land area, and enable the region to maintain a certain grain production capacity and grain self-sufficiency rate. At the same time, it is necessary to improve the urban-rural relationship in the county and surrounding areas , promote the orderly flow and optimal allocation of urban and rural resource

elements, promote urban-rural integration and complementary development, and achieve coordinated and stable regional population-cultivated land-grain systems.

6.2. Conclusion

From 2000 to 2020, the number of rural population in all regions of the country has been declining in a straight line, with the rate of decrease showing a regional pattern of high rate in the central and northeastern regions and relatively low rate in the eastern and western regions. The changes in cultivated land area in counties in different regions of the country varied greatly. Except for the eastern region, the cultivated land area in counties in other regions has increased, and the distribution of cultivated land has become more unbalanced; grain output has shown an overall growth trend, with insufficient growth potential in grain output in the eastern region and significant growth in grain output in other regions. From the perspective of average quantity, the per capita cultivated land area of the rural population in counties across the country has increased overall, and the center of gravity of per capita cultivated land area has continued to move toward the northeast; the per capita grain output of counties varies greatly, with higher grain yields in eastern regions such as East China, South China and the middle reaches of the Yangtze River in the central region, which was the center of gravity of per capita grain output in China.

The coupling patterns of population-cultivated land-food system changes reflected by the per capita cultivated land area and per-land grain output in rural areas were mainly manifested in four types, showing certain differences in spatial pattern distribution. Specifically, the "simultaneous increase" pattern was mainly concentrated in Northeast China, North China, Jianghuai region, eastern Inner Mongolia, northern Shaanxi, Hunan and parts of Jiangxi, mainly in traditional agricultural areas. The "reduced population, reduced land, and increased grain" pattern of reduced per capita cultivated land area and increased per-land grain output in rural areas was mainly distributed in the middle and upper reaches of the Yellow River and Yunnan, Guizhou, Sichuan, Guangxi and other regions in the southwest, which were greatly affected by desertification and rocky desertification. The pattern of increased per capita cultivated land area in rural areas and reduced per-land grain output was mainly distributed in northwest Sichuan, Xinjiang and other regions and most areas of the southeast coastal area, where population urbanization was faster than land urbanization. The "simultaneous reduction" type was scattered in northeastern Zhejiang Province, southeastern Fujian Province, and parts of northern Tibet.

Based on the establishment of a dynamic evolution analysis framework for a semi-open complex system of population, cultivated land and food, this study analyzed the characteristics of changes in total amount and in per capita/unit amount of the population-cultivated land-food system in China's county-level rural areas, and proposed differentiated planning strategies for county-level rural areas with different change coupling patterns from the perspective of population-cultivated land-food system coordination, which could provide theoretical significance and practical reference value for ensuring China's cultivated land and food security, supporting the high-quality promotion of new urbanization and agricultural modernization based on counties.

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