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Potential imbalanced differences of grain production in the sustainable development of county cities—a case study of Jiangsu Province

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Introduction: Grain production at the regional level is related to the strategic development orientation of the country as a whole, and maintaining the stability of grain production is of great importance in ensuring the sustainable development of the food system. Studying the potential imbalance differences resulting from the spatial and temporal development of grain production and its driving factors will help to reduce the contradiction between the rapid development of the urban economy and the inappropriate use of arable land resources, thus coordinating regional agricultural development and further clarifying the direction and focus of future food security construction work.

Methods: This study focuses on the potential imbalance differences based on spatial and temporal development of grain production in Jiangsu Province during the period 1990–2020, and explores the spatial and temporal patterns and driving mechanisms of grain production spatial autocorrelation model and spatial error model are applied to analysis the spatial and temporal characteristics of grain production and security in Jiangsu Province and their influencing factors.

Results: The results are as follows: (1) The total amount of food in Jiangsu Province increased by 17.36% during the 30-year period, but the growth rate was lower than the national average. (2) Regional differences are significant, with a significant decline in grain production in southern Jiangsu and growth in northern and central Jiangsu. (3) The center of gravity for grain production has shifted to northern Jiangsu. (4) Grain production is significantly correlated with socio-economic factors such as per capita ownership, sown area, irrigated area, and cultivated area.

Discussion: To ensure the sustainability of food production in the future, attention should be paid to the risk of imbalance in regional food production, coordination of socio-economic factors, promotion of efficient agricultural production, improvement of the relevant policy system and optimization of the food production system.

KEYWORDS

unbalanced differences, grain production, spatial and temporal patterns, influencing factors, Jiangsu Province

1 Introduction

Grain production has always been one of the core issues of global sustainable development, especially in the context of a rapidly changing economic and environmental environment, and is an important cornerstone for ensuring national security and social stability. Despite the increase in global grain production, the uneven spatial distribution of food and regional food insecurity remain critical (Mumuni and Aleer, 2023). In China, grain production has always been a top national priority, and the Chinese government has continuously promoted a national policy to ensure food security. In recent years, although China's total grain production has consistently ranked first in the world, it has faced many challenges in terms of grain production and food security, such as uneven regional distribution of production, fragmentation of land use, and differentiation between places of grain production and consumption (Fei et al., 2023). Various studies have explored regional grain production from multiple perspectives. one study simulated future grain production at the provincial level by constructing causal feedback between food supply, demand, production inputs, and policy factors, which shows that the future grain production situation will deteriorate with urbanization and demand growth, with less and less room for productivity improvements and high demand (Xu and Ding, 2015). Conversely, growth in overall grain production emerges as a key factor in mitigating production risks, enhancing the food security situation as the capacity for regional food supply strengthens.

However, as the center of gravity of the grain production shifts, it will hurt ecosystem stability and economic development in the shifting regions (Zhang et al., 2023). Simultaneously, the mechanization of agricultural production is a key factor in enhancing grain supply capacity and efficiency, furthering the agricultural modernization process (Liu and Li, 2023). Optimizing the productivity of the agricultural population (Jiao et al., 2018), fertilizer application efficiency, and water and nutrient use efficiency can effectively increase grain production (Jiangchuan et al., 2020). It has been argued that densely populated areas have sufficient financial and labor resources, but their responsibility for food supply is relatively limited. At present, there have been relevant studies on temporal panel data of grain production, but most of them focus on large-scale assessments at the national or watershed scale, often ignoring the spatial heterogeneity within the region, with unclear spatial positioning and insufficient localization, which may lead to a lack of relevance and accuracy of the assessment results (Hu et al., 2023). The county and district levels are the grassroots administrative units in China, and studying grain production at the county level can help better optimize the overall food strategy pattern and implement relevant policies (Liu and Xu, 2023). Studying grain production at the county level can help optimize the overall food strategy pattern and implement related policies. However, research at this level is not yet complete and there is a need for deeper analysis based on traditional research.

Given this, this study is to analyze in depth the spatial and temporal development of grain production in the counties of Jiangsu Province during the period 1990–2020, to explore its potential imbalance differences, and to reveal the factors that may affect this risk. The specific objectives of this paper are as follows: (1) To analyze the spatial and temporal changes of grain production in the counties of Jiangsu Province in the past 30 years. (2) To reveal the typical characteristics of the development of their grain production pattern. (3) To explore the main influencing factors of the potential imbalance difference phenomenon in this context. The research results will provide rigorous and scientific data support and empirical references for optimizing and improving the sustainability of grain production in Jiangsu Province and other regions.

2 Materials and methods

2.1 Study area

Located on the east coast of China (116°18′-121°57′ longitude, 30°45′-35°20′ latitude), Jiangsu Province is the most densely populated of China's 23 provinces and is also the most important grain supply area among the 13 major grain-producing areas, with a stable annual grain production of more than 35 billion kilograms, with 3.73% of the country's arable land, it supplies 5.49% of the country's food, with a self-sufficiency rate of 110.5%. Since the 13th 5-Year Plan, Jiangsu has been deeply implementing the strategy of "hiding grain in land and technology," and promoting the continuous improvement of grain production capacity through the implementation of high-standard farmland construction, seed industry upgrading projects, as well as the early start of the pilot project of mechanization of the whole process of grain production, etc. However, the per capita arable land area of Jiangsu is <667 square meters, a typical phenomenon of "more people, less land," even if its arable land is rich in reserve resources, and food consumption, grain production conditions are diverse, which will inevitably lead to regional development imbalance, and thus the risk of food security system, the choice of which as the object of study has a fairly representative (Liu and Zhou, 2021). Grain production in Jiangsu Province is characterized by high productivity, diversified grain varieties, advanced agricultural technology and an important contribution to national grain production. Its significantly differentiated production patterns within the region reflect both the differences in economic and agricultural development within the province and epitomize the common problems faced by other provinces in China. Therefore, choosing Jiangsu Province as the object of study can provide insight into the regional differences and development trends of China's grain production, and provide important case studies and strategic references for promoting the balanced development of national grain production.

Since the administrative boundaries of some counties and Districts have been adjusted and merged in the past 30 years, this study takes the administrative boundaries of counties in Jiangsu Province in 2020 as the starting point, and corrects the data of other cross-section years, while referring to the Rural Statistical Yearbook of Jiangsu Province, and the Municipal Districts of each City are statistically analyzed according to an administrative unit. Based on the above, it is determined that the total number of County administrative units involved in this study is 72, and the main areas are divided into three regions: southern Jiangsu, central Jiangsu and northern Jiangsu. The scope and geographical location of the study area are shown in Figure 1.

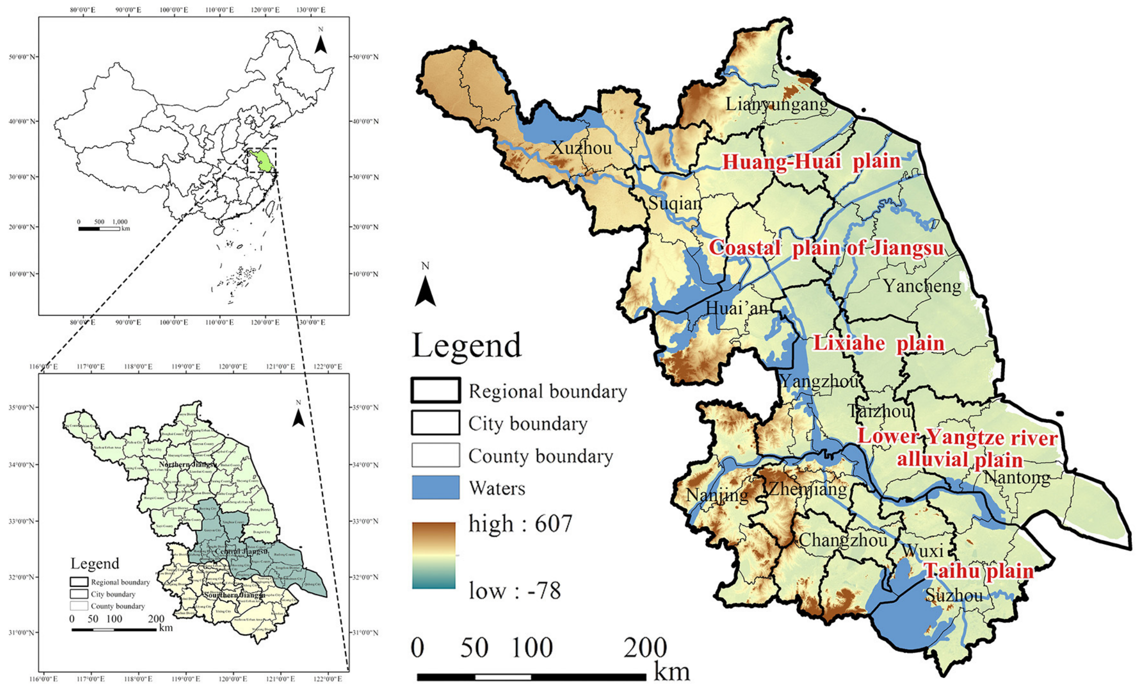

FIGURE 1
Schematic representation of the scope and geographic location of the study area.

2.2 Data sources

In this study, 1990–2020 is selected as the research period, which is the most drastic change of grain producing in Jiangsu Province since reform and opening up, and it is also convenient to highlight the current development of grain production in Jiangsu Province (Han and Yan, 2022). Data sources include: ① Socio-economic data: from Jiangsu Statistical Yearbook, Jiangsu Rural Statistical Yearbook, China County (municipal) Socio-Economic Statistical Yearbook, as well as public data from local municipal statistical yearbooks and statistical bureaus, to obtain the province's grain production data at the County and District levels, data on the sown area of grain, the amount of fertilizer applied to agriculture, and data on population. ② Administrative division data.

2.3 Research methodology

2.3.1 Spatial autocorrelation analysis

In this paper, the spatial autocorrelation of spatial grain production data over geospatial space in Jiangsu counties is calculated by using Global Moran's I through the ArcGIS10.8 platform. This approach is particularly suitable for identifying and analyzing the spatial clustering characteristics of geographic data, and is important for understanding the spatial distributional differences in food production between different regions in Jiangsu Province and the potential factors behind them. The calculation formula is as follows:

$$I = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(x_i - \bar{x})(x_j - \bar{x})}{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}\sum_{i=1}^{n}(x_i - \bar{x})^2}$$

Where: the value of I is between -1 and 1. When the value of I is positive, it indicates that the spatial data have positive autocorrelation, i.e., similar eigenvalues are more likely to appear in geographic locations near each other; when the value of I is negative, it indicates that the spatial data have negative autocorrelation, i.e., similar eigenvalues are more likely to appear in geographic locations farther away from each other; and when the value of I is close to 0, it indicates that the spatial data are randomly distributed. Where n represents the number of County units, x_i and x_j represent the observed values of spatial units, respectively; x represents the average of the observed values; w_{ij} represents the spatial adjacency matrix between County units i and j in the study area.

In addition, this study applies the *Getis-Ord Gi** hot spots analysis to calculate the local spatial autocorrelation indexes of grain production data within the counties of Jiangsu. The obtained *z*-score and *p*-values can be used to determine the location where spatial clustering of high or low value elements occurs, which in turn can be used to determine the degree of aggregation or dispersion of each County's data among neighboring counties in space (Lv et al., 2022). The *Gi** statistic returned for each element in the dataset is the *z*-score. For positive *z*-score that are statistically significant, the higher the *z*-score, the tighter the clustering of high values (hot spots), and vice versa. By analyzing local spatial autocorrelation indices, it is possible to identify areas of county agglomeration with above-average food production. These hotspot areas are indicative of the geographic clustering characteristics of high yields and are critical to understanding the spatial distribution patterns of food production within the region. Cold spot areas, as opposed to hot spots, reflect below-average food production capacity. This information is critical for early identification of underproductive regions, assessment of food security risks, and taking appropriate remedial measures.

*Getis-Ord Gi** is calculated as follows:

$$G_i* = \frac{\sum_{j=1}^{n} w_{i,j}x_j - \overline{X}\sum_{j=1}^{n} w_{i,j}}{S\sqrt{\frac{\left[n\sum_{j=1}^{n} w_{i,j}^2 - \left(\sum_{j=1}^{n} w_{i,j}\right)^2\right]}{n-1}}}$$

where $x_j$represents the attribute value of element j, $w_{i,j}$represents the spatial weight between elements i and j, n represents the total number of elements, and:

$$\overline{X} = \frac{\sum_{j=1}^{n} x_j}{n}$$

$$S = \sqrt{\frac{\sum_{j=1}^{n} x_j^2}{n} - (\overline{X})^2}.$$

2.3.2 Center of gravity shift model

The center of gravity shift model is used to describe and quantify the change in the location of the centroid of a phenomenon in geographical space. In this study, the centroid of total grain production in Jiangsu County is considered as the average or equilibrium point of grain production in the region (Xia et al., 2023).

The formula for the center of gravity calculation is as follows:

$$C_x = \sum (U_x\, W) / \sum W$$

$$C_y = \sum (U_y\, W) / \sum W$$

where C_x represents center of gravity transverse coordinate, C_y represents center of gravity vertical coordinate, U_x represents unit transverse coordinate, U_y represents unit vertical coordinate, W represents weight, which usually correspond to indicators of quantity, production, etc. of a phenomenon.

Where Σ denotes summation and the weights usually correspond to indicators of quantity, production, etc. of a phenomenon.

2.3.3 Spatial error modeling

The spatial error model (SEM) is a statistical model for spatial data analysis that takes into account the effects of spatial correlation and spatial heterogeneity (Yildirim and Kantar, 2020). SEM is a generalized linear model that is particularly well-suited to deal with situations in which the dependent variable is spatially auto correlated (Grodzicki and Jankiewicz, 2022). In this study, based on the data of grain sown area, grain production, agricultural fertilizer application, and household population at the County level in Jiangsu Province from 1990 to 2020, the main driving factors affecting the grain supply balance are explored through the spatial error model.

The specific expression for SEM is as follows:

$$Y = X\beta + \lambda W\varepsilon + u.$$

Where Y represents the dependent variable, X represents the matrix of the independent variables, β represents the vector of coefficients of the independent variables, W represents the spatial weight matrix, ε represents the spatial error term, and represents the non-spatial error term.

3 Results

3.1 Changes in the timing of grain production

3.1.1 Grain production

As shown in Figure 2, the total grain production of Jiangsu Province from 1990 to 2020 increased from $3{,}156 \times 10^8$ kg in 1990 to $3{,}697 \times 10^8$ kg in 2020, an increase of about 17.36%. However, its average annual growth rate is 0.58, much lower than the national average (1.75%). Despite fluctuations in the intervening years, it shows an overall growth trend. At the regional level, grain production varied from year to year in southern, central, and northern Jiangsu. In southern Jiangsu, grain production gradually decreased from 898×10^8 kg in 1990 to 402×10^8 kg in 2020, a decrease of 55.24%, while in central Jiangsu, grain production gradually increased from 791×10^8 kg in 1990 to 908×10^8 kg in 2020, an increase of about 14.82%. In northern Jiangsu, grain production gradually increased from $1{,}467 \times 10^8$ kg in 1990 to $2{,}387 \times 10^8$ kg in 2020, an increase of 62.87%. There are significant differences in grain production among regions within Jiangsu Province, with the most pronounced differences between the southern and northern parts of the province.

3.1.2 Per capita grain production

The total population of Jiangsu Province is nearly 90 million, with three cities exceeding 9 million, while the least populated city has <4 million, making the total population large but unevenly distributed. Therefore, the per capita grain production was calculated to further evaluate the grain production situation. Per capita grain production in Jiangsu Province shows an overall decreasing trend over the 30-year time span, decreasing from 457.26 kg in 1990 to 465.62 kg in 2020, with a growth rate of about 1.83%; per capita grain in southern Jiangsu shows a decreasing trend: from 398.83 kg in 1990 to 145.11 kg in 2020. the rate of change is as high as 63.67%. In contrast, the per capita grain in central Jiangsu shows a fluctuating upward trend: from 465.40 kg in 1990 fluctuating increase to 532.21 kg in 2020, an increase of

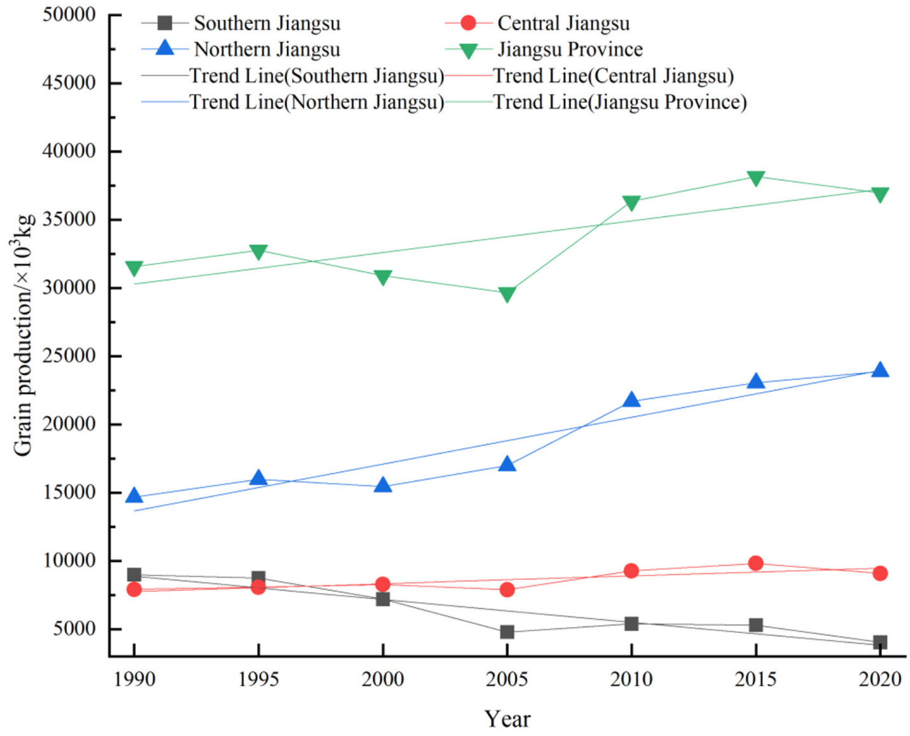

FIGURE 2
Changes in grain production in Jiangsu Province.

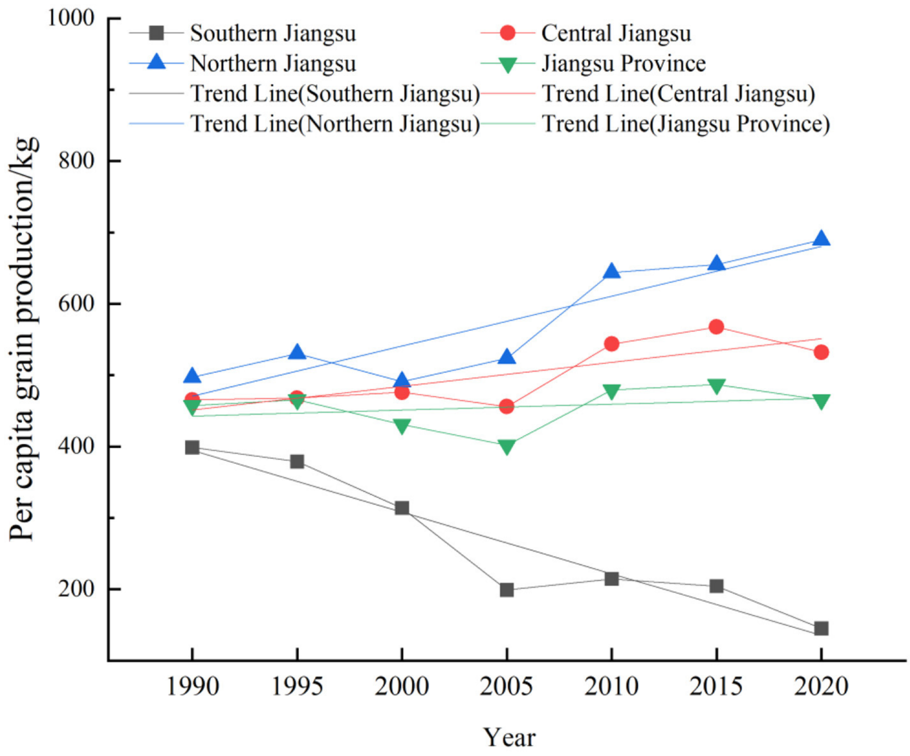

FIGURE 3
Changes in per capita grain production in Jiangsu Province.

14.36%. In northern Jiangsu, the per capita grain shows a gradual increasing trend: from 497.16 kg in 1990 to 689.50 kg in 2020, an increase of 38.65%. Despite the overall trend of steady growth in per capita grain production in all counties of the province, there are significant differences between different regions, especially between southern and northern Jiangsu, and the potential imbalance between regions has come to the fore, which may be related to the imbalance between economic development and agricultural production conditions within the region (Figure 3).

3.1.3 Patterns of temporal changes in grain production

Both total grain production and per capita grain production have shown an increasing trend over the past 30 years. Central and northern Jiangsu have shown positive growth in both aspects. In terms of total grain production, southern Jiangsu has shown a significant downward trend, while central and northern Jiangsu have shown growth. In terms of per capita grain production, the decline was more pronounced in southern Jiangsu, while northern Jiangsu shows greater growth.

In order to further explore the causes and characteristics of this phenomenon, this study further analyzes the spatial pattern of grain production and grain production to better understand how resources are allocated and used in different regions and how this affects grain production and per capita grain production. At the same time, socio-economic factors such as the effective irrigated area, the size of the agricultural population, the area of arable land, the amount of fertilizer applied, and the total power of agricultural machinery have an important impact on grain production and distribution. Spatial analysis can reveal how these factors play out in different regions, thereby affecting grain production and sustainability. Considering spatial patterns not only helps to understand the current situation, but is also essential for predicting future trends and planning long-term sustainable development strategies. A deeper understanding of the differences between regions can provide a more comprehensive guide to the development of more effective policies and strategies.

3.2 Spatial variation in grain production

3.2.1 Evolution of spatial patterns of grain production

The *Global Moran's I* values of grain production in the counties of Jiangsu Province in each 5-year period from 1990 to 2020 are 0.2394, 0.2845, 0.3158, 0.4331, 0.4891, 0.4923, 0.5519, and the spatial autocorrelation of grain production data in counties in each period shows a highly significant positive correlation, indicating that the spatial correlation between grain productions in different periods is gradually increasing. Is a highly significant positive correlation, indicating that the spatial correlation of grain production between different periods is gradually increasing.

The *p*-value and *z*-value of grain production in the counties of Jiangsu Province and grain production in each 5 years of seven time periods between 1990 and 2020 were derived from the *Getis-Ord Gi** model, and the counties were categorized into level 1 hot spots (99% confidence level), level 2 hot spots (95% confidence level), level 3 hot spots (90% confidence level), insignificant, level 3 cold spots, level 2 cold spots, and level 1 cold spots based on each County in turn.

In the past 30 years (1990–2020), the hot spots of grain production in Jiangsu Province were mainly distributed in northern Jiangsu, and the distribution pattern changed significantly from year to year. Before 2000, the hot spots were concentrated in a small area in northern Jiangsu and were relatively scattered. The first-level hot spots were distributed in Xinyi County; however, after 2000, the clustering area of the hot spots gradually expanded, with Yancheng City as the center, extending from Xinyi County in the north to Xinghua County in the south. From 2005, the hot spots clustering was connected into a complete band, and the first-level hot spots area was gradually expanded to include Yancheng Municipal District and Xinghua County, and the hot spots was extended to the whole territory of northern Jiangsu, Huang-Huai Plain, Coastal Plain of Jiangsu and Lixiahe Plain were all involved, mainly concentrated in the junction of Lixiahe Plain and Coastal Plain of Jiangsu, and the hot spots clustering was significantly newly improved, and the hot spots zone area was enlarged. In 2005–2015, the change of hot spots clustering was not obvious, and the area of the hot spots zone remained the same; however, in 2020, the hot spots area began to expand to the major grain-producing areas in the Huang-Huai Plain and the Lixiahe Plain region, including Sihong County, Hongze District, and Xuyi County, among others.

On the other hand, cold spots mainly accumulate in central and southern Jiangsu, showing a cluster-like layout and gradually expanding during 1990–2020. In the 10 years from 1990 to 2000, cold spots are mainly concentrated in the Lower Yangtze River Alluvial Plain around Zhenjiang Municipal District, and there is no obvious change in their agglomeration pattern; from 2005, the importance of cold spots in the Taihu Plain increases, and the cold spots gradually spread to the Taihu Plain, represented by Changzhou City, Wuxi City, and Suzhou City. By 2020, the cold spots have covered the whole of Zhenjiang City except Yangzhong County, the whole of Changzhou City, as well as Wuxi Municipal District and Changshu County, and their significance has increased (Figure 4).

3.2.2 Evolution of the spatial pattern of rates of change in grain production

The evolution of spatial agglomeration hot spots in the rate of change of grain production per 5 years in Jiangsu counties from 1990 to 2020 is shown in Figures 5A–F. Over the past 30 years, the overall spatial pattern has changed more obviously, except for Ganyu District and Qingjiangpu District, northern Jiangsu shows a growing trend, especially in areas such as Xuzhou municipal Jurisdiction and Lianyungang municipal Jurisdiction, which show significant hot spots of agglomeration; Central Jiangsu, especially the areas near the Lixiahe Plain, shows a growing trend, while the Lower Yangtze River Alluvial Plain near the southern Jiangsu shows a declining trend; southern Jiangsu shows a declining trend before the change was not significant before 2000, but since the new century, grain production in areas such as the Taihu Plain and the Lower Yangtze River Alluvial Plain have been in a state

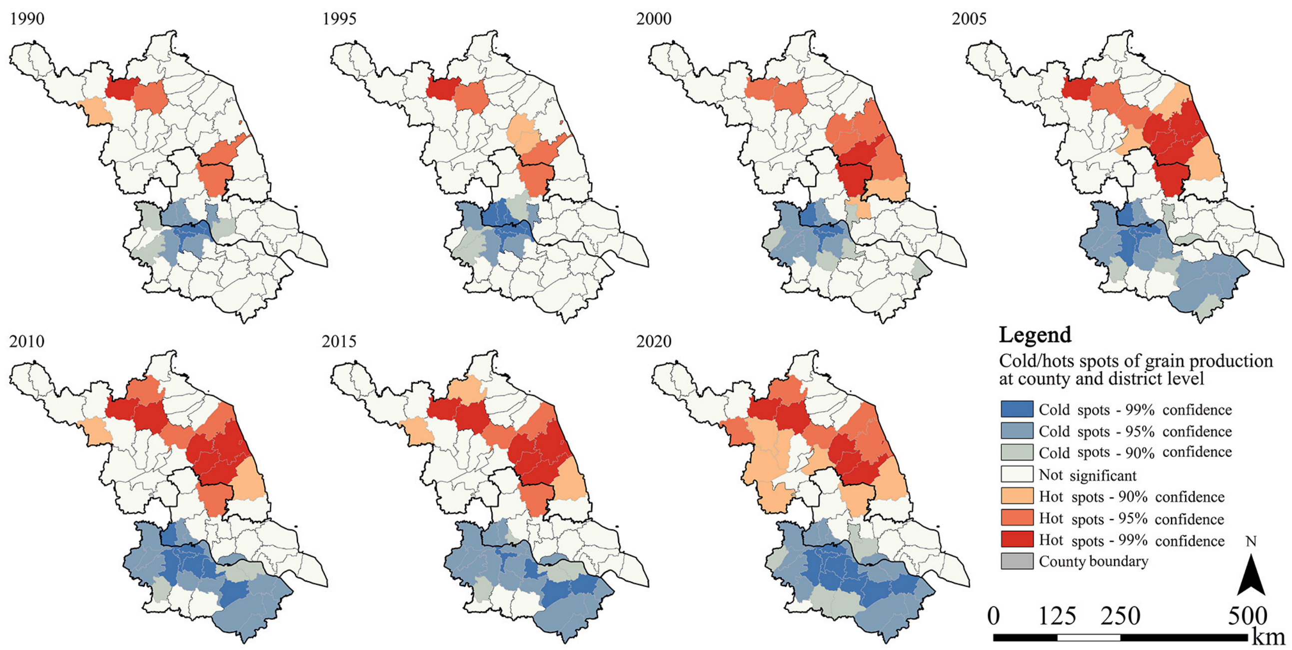

FIGURE 4
Cold/hots spots of spatial concentration of grain production at the county level in Jiangsu counties, 1990–2020.

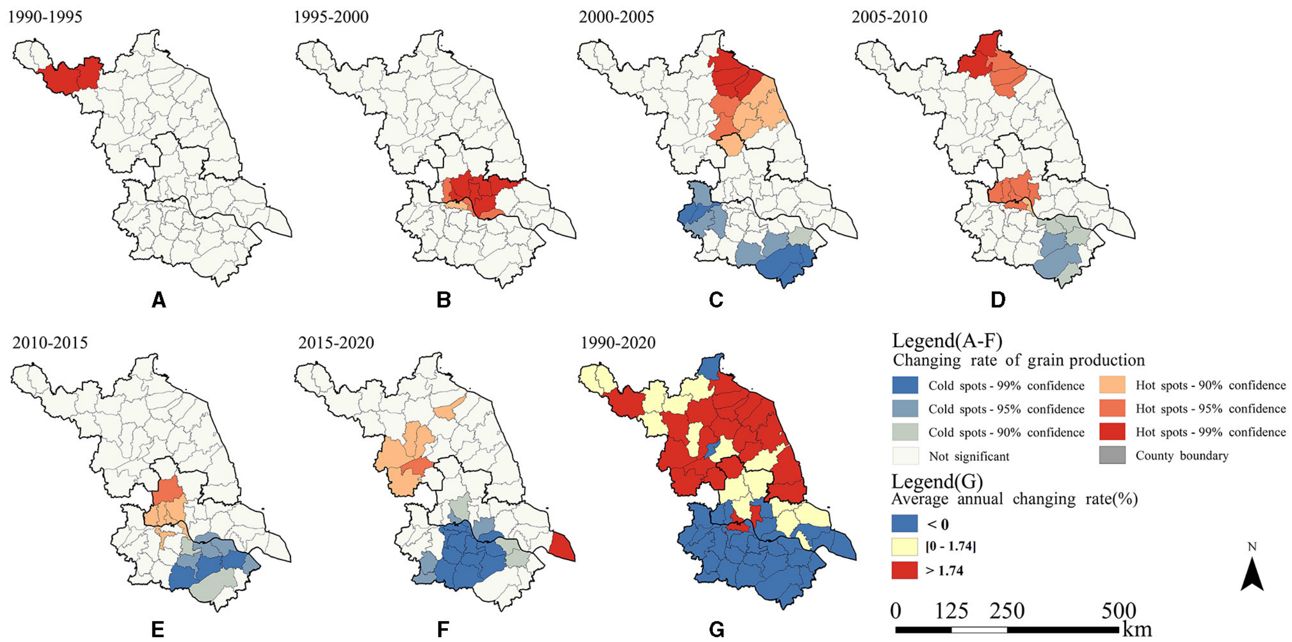

FIGURE 5
(A–G) Evolution of spatial agglomeration hotspots in the rate of change of grain production per 5 years in Jiangsu counties, 1990–2020.

of long-term decline, and all of them passed the significance test of cold spots clustering from 2000 to 2020. Based on the grain production data in 1990 and 2020, the average annual rate of change is classified into three classes: <0, 0–1.74% (1.74% is China's national average), and >1.74%. As can be seen in Figure 5G, during the period 1990–2020, counties and Districts with an average annual rate of change in grain production <0 are mainly concentrated in the Taihu Plain and part of the coastal Plain in southern Jiangsu, accounting for 45.83% of the province; only 31. Ninety-four percent of the counties and Districts with an average annual growth rate of grain production higher than the national average are mainly located in the Huang-Huai

Plain in northern Jiangsu, the Lixiahe Plain, Coastal Plain of Jiangsu, and the northern region of the Lower Yangtze River Alluvial Plain.

3.2.3 Evolution of the spatial pattern of per capita grain production

During the period 1990–2020, the per capita grain production data of Jiangsu counties in seven-time study sections Moran I is 0.1248, 0.1360, 0.1982, 0.4104, 0.4230, 0.4244, 0.4965, which indicates that the spatial correlation of per capita grain has gradually increased over the past 30 years, especially in 2020 to reach the highest, for the nearly four times of 1990. Local autocorrelation analysis using ArcGIS10.2 was used to obtain the LISA spatial aggregation map (Figure 6), and the results show that: before 2000, the high-high aggregation area was mainly distributed in the Huang-Huai Plain and Coastal Plain of Jiangsu, and the low-low aggregation area was mainly distributed in the Lixiahe Plain and surrounded by a small number of high-low aggregation areas. In 2000, the center of gravity of the high-high aggregation was shifted to the Coastal Plain of Jiangsu and gradually connected with northern Jiangsu. After 2000, the center of gravity of high-high agglomeration shifted to the Coastal Plain of Jiangsu and gradually connected with northern Jiangsu, showing an "L" shape distribution. The center of gravity of the low-low agglomeration area shifted to the Taihu Plain in southern Jiangsu and gradually expanded, covering almost the entire southern Jiangsu by 2020. Only a small number of high-low agglomerations and low-high agglomerations changed sporadically.

3.3 Evolution of grain production patterns

3.3.1 Spatial and temporal characteristics of grain production

In this study, the per capita grain production in Jiangsu counties from 1990 to 2020 is divided according to the following classification criteria.

Critical food-deficit counties (per capita grain <150 kg), general food-deficit counties (per capita grain 150–300 kg), food supply and demand balanced counties (per capita grain 300–400 kg), general food-surplus counties (per capita grain 400–600 kg), and adequate food-surpluses counties (per capita grain >600 kg) as a criterion for categorizing food demand (Table 1; Rohr et al., 2021). The basis for this classification reflects the basic situation of different regions in terms of food supply and demand, and is based on the food production and consumption patterns prevailing in Jiangsu Province and other regions of China. Taking into account the differences in the level of economic development and population density within China and Jiangsu Province, this classification contributes to an in-depth understanding of the imbalances in food production and consumption within the region (Hu et al., 2023).

The results shows that the number of critical food-deficit counties gradually increased with slight fluctuations, and the number of general food-deficit counties gradually decreased before 2000, rapidly increased in 2000–2005, and then stabilized. Food supply and demand balanced counties show an increasing and then decreasing trend, reaching a peak of 11 counties in 2000, with only two counties remaining in 2020. The number of general food-surplus counties has gradually declined over the past 30 years, with only about ½ of the 1990 number remaining in 2020. Adequate food-surpluses counties fluctuate slightly through 2005, increase rapidly from 2005 to 2010, and then stabilized.

From 1990 to 2020, the distribution of per capita grain production in Jiangsu counties generally shows the distribution of northern Jiangsu > central Jiangsu > southern Jiangsu (Figure 7). Before 2005, food-deficit counties (including critical food-deficit counties and general food-deficit counties) were scattered, with a small number of sporadic distributions in northern Jiangsu and part of the southern Jiangsu. After 2005, there is a more obvious clustering of food-deficit counties in southern Jiangsu, and its spatial distribution pattern is similar to that of the cold point clustering of grain production; Most of the general food-surplus counties have been gradually transformed into adequate food-surpluses counties over the past 30 years, mainly in Huang-Huai Plain and Lixiahe Plain; adequate food-surpluses counties were sporadically scattered before 2005, but then gradually formed a wide range of clustering in northern Jiangsu, and by 2020, 68.75% of the counties in northern Jiangsu had become adequate food-surpluses counties, roughly the same pattern as the hot spots clustering of grain production.

3.3.2 Center of gravity shift model for grain production

From 1990 to 2020, the center of gravity of grain production in Jiangsu Province experienced significant migration, reflecting changes in the center and strength of grain production in the region. This change began in Gaoyou County and gradually moved in a north-west direction to Baoying County in the direction of $18°38'$ northwest, showing an overall northward trend, with a total migration distance of 47.23 km. Importantly, this migration not only reflects changes in the geographic distribution of food production, but also reveals the possible impacts on the spatial pattern of food production of factors such as economic development, agricultural policy adjustments and resource allocation options. In particular, the center of gravity of the general food-surplus counties shifted northward to Huai'an District, with a migration distance of 83.12 km, indicating the enhanced position of the northern part of Jiangsu Province in terms of grain production, and at the same time reflecting the widening of the difference in grain production capacity between the northern and southern regions. This migration of the center of gravity is not only crucial to understanding regional food production dynamics, but also provides a basis for formulating regional food security measures and optimizing the allocation of agricultural resources.

The change in the center of gravity of the general food-surplus counties is relatively small, migrating from Baoying County to Gaoyou County in the beginning, then to Huai'an District in the north, and finally to Jinhu County in the south, with a total migration distance of 20.05 km. However, the change of the center of gravity of the food-deficit counties (including the general food-deficit counties and the adequate food-surpluses counties) is more

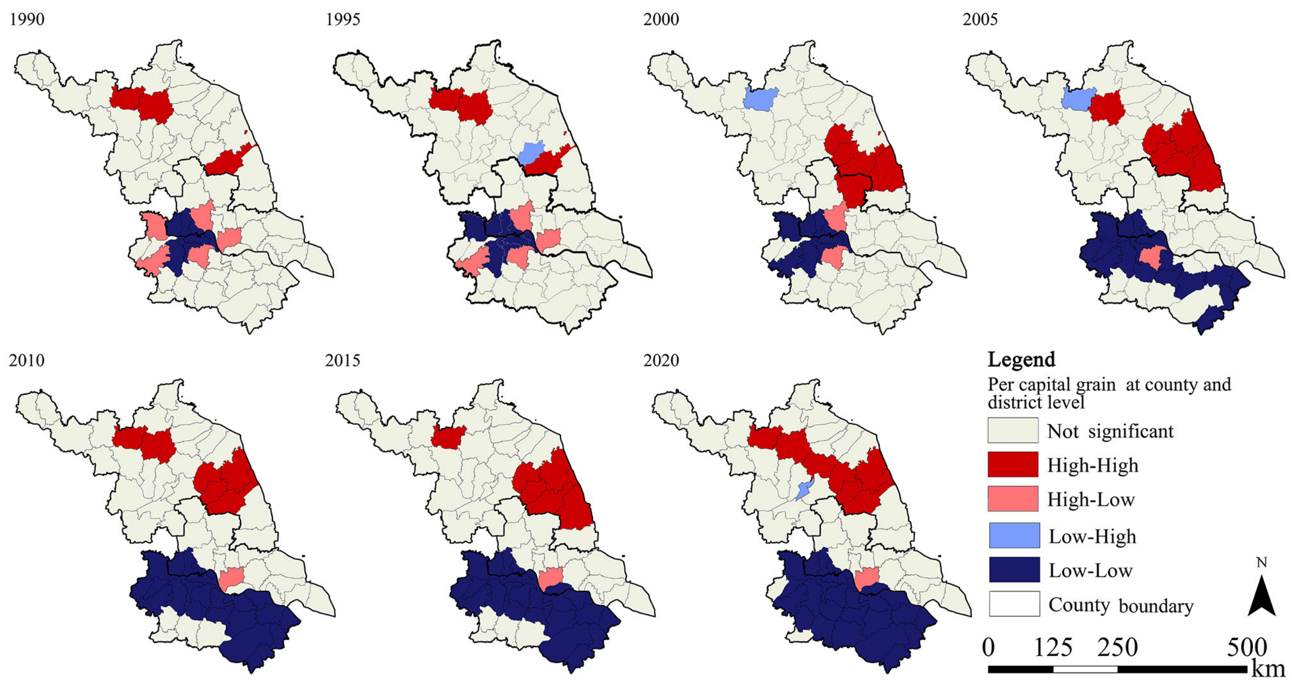

FIGURE 6
LISA cluster of per capital grain at county level in Jiangsu counties, 1990–2020.

TABLE 1 Capital grain production at county level in Jiangsu counties, 1990–2020.

Year	Critical food-deficit counties	General food-deficit counties	Food supply and demand balanced counties	General food-surplus counties	Adequate food-surpluses counties
1990	6 (8.33%)	6 (8.33%)	5 (6.94%)	36 (50.00%)	19 (26.39%)
1995	7 (9.72%)	5 (6.94%)	5 (6.94%)	35 (48.61%)	20 (27.78%)
2000	8 (11.11%)	3 (4.17%)	11 (15.28%)	35 (48.61%)	15 (20.83%)
2005	10 (13.89%)	12 (16.67%)	10 (13.89%)	21 (29.71%)	19 (26.39%)
2010	8 (11.11%)	11 (15.28%)	6 (8.33%)	19 (26.39%)	28 (38.89%)
2015	9 (12.50%)	13 (18.06%)	3 (4.17%)	18 (25.00%)	29 (40.28%)
2020	12 (16.70%)	12 (16.67%)	2 (2.78%)	17 (23.61%)	29 (40.28%)

complicated, which has remained within Taizhou City for the past 30 years, and only migrated to Jingjiang County in 2005, and within Taixing County for the rest of the years, with a total migration distance of 8.70 km and a migration direction of 62°00′ north by east.

The center of gravity of food supply and demand balanced counties changes most dramatically, migrating within Rugao County during 1990–1995, followed by a series of migrations in the following years, including from Rugao County to Gaoyou County during 1995–2000, from Gaoyou County to Suqian Municipal District during 2000–2005, from Suqian Municipal District to Hongze District during 2005–2010, and from Hongze District to Jiangning District during 2010–2015. From Hongze District to Jiangning District and finally to Yixing County during 2015–2020. The whole migration process passed through the Coastal Plain of Jiangsu, Lixiahe Plain, and finally arrived at the Taihu Plain, with a total migration distance of 134.70 km and a direction of 45°34′ south by west (Figure 8).

3.4 Factors affecting grain production

There are significant spatial and temporal differences in grain production among different regions in Jiangsu Province, the most obvious being the significant increase in grain production in northern Jiangsu and the significant decrease in per capita grain production in southern Jiangsu, which to some extent affects the balance of grain production status among regions. The geographical migration of the center of gravity of grain production and its dynamic changes highlight the complexity of grain production in Jiangsu Province. At the same time,

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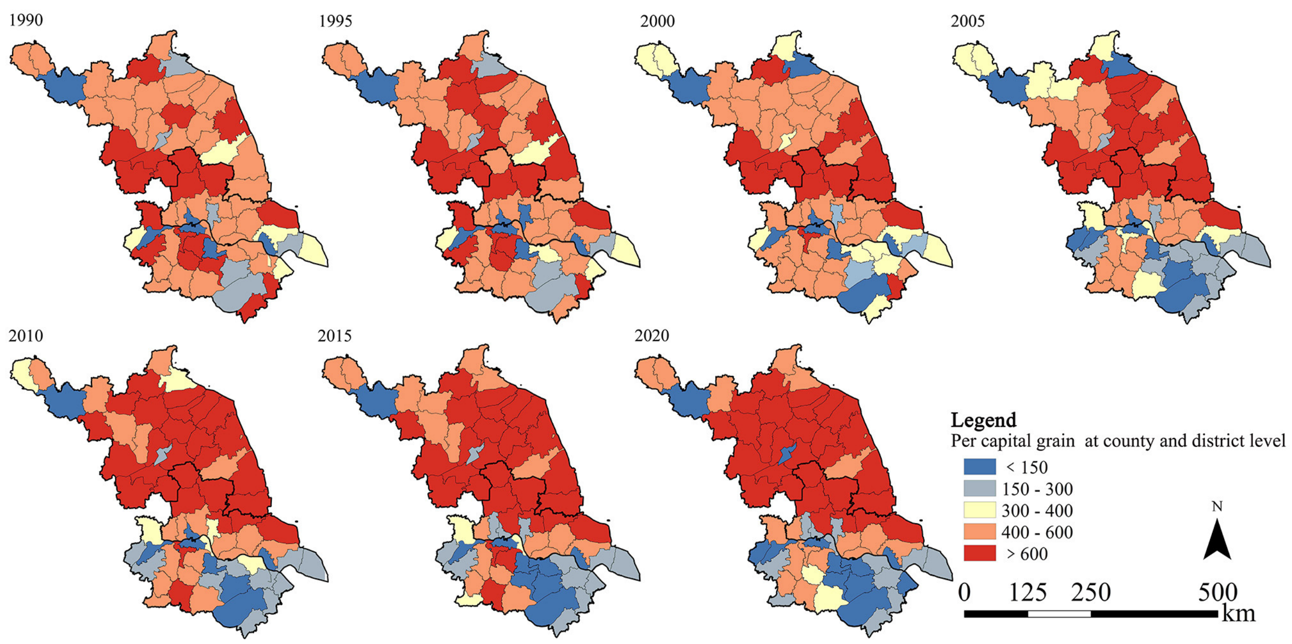

FIGURE 7
Spatial pattern of per capital grain at county level in Jiangsu counties, 1990–2020.

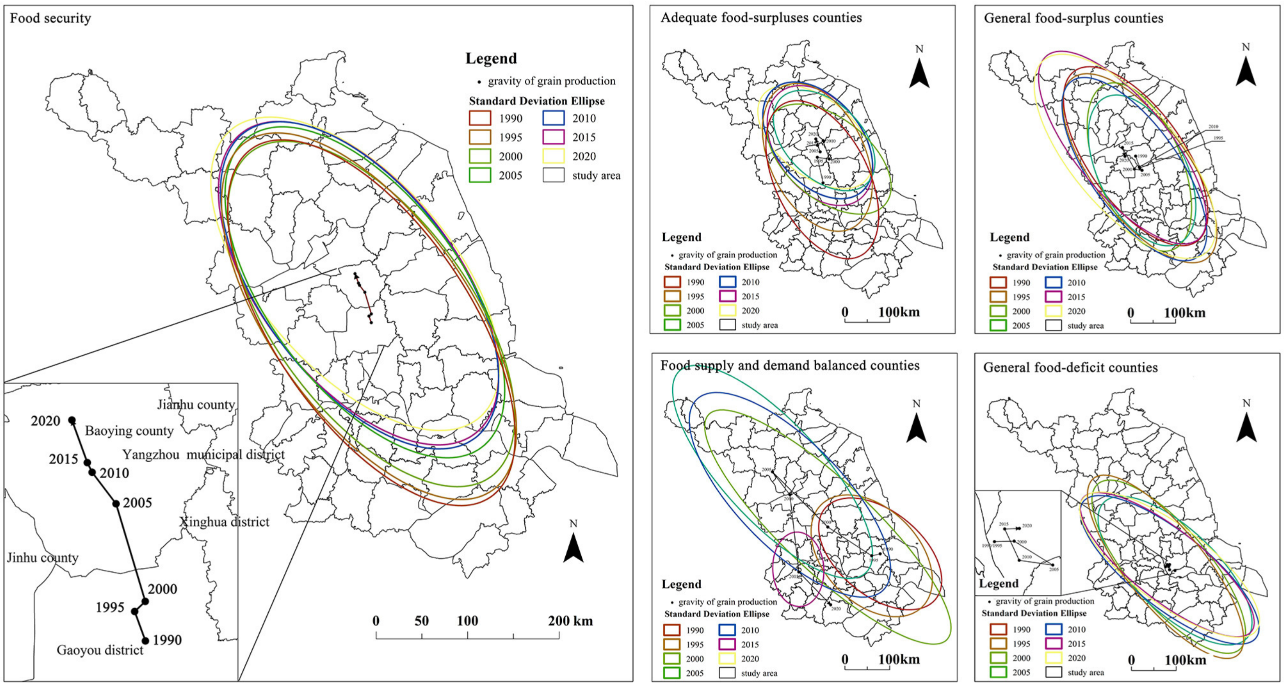

FIGURE 8
Gravity center shifting routes for grain production in Jiangsu counties, 1990–2020.

such potential imbalances also exacerbate food security risks to some extent.

To further explore the causes of these potential imbalance discrepancies, the key factors that may affect grain production in Jiangsu counties from 1990 to 2020 are carefully analyzed through SEM modeling. The influential factors analyzed include, but are not limited to, the variables of per capita grain production, grain sown area, effective irrigated area, number of the agricultural population, cultivated land area, fertilizer application, and total power of agricultural machinery. The regression coefficients of these seven

TABLE 2 Estimated results of influencing factors that grain production at country level in Jiangsu counties, 1990–2020.

Year	1990	1995	2000	2005	2010	2015	2020
Model variables	Coef.	Coef.	Coef.	Coef.	Coef.	Coef.	Coef.
Grain production per capita	565.89***	629.61***	747.00***	846.79***	798.81***	795.01***	762.50***
Grain sown area	3.95***	4.84***	5.17***	4.96***	5.41***	5.66***	5.66***
Effective irrigation area	6573.30***	2537.83***	7447.41***	7871.89***	9616.09***	8972.68***	9227.92***
Number of agricultural population	3837.17***	4180.14***	3980.73***	4093.41***	5229.84***	5826.53***	5381.27***
Cultivated land area	5.38***	7.13***	5.62***	5.85***	6.99***	7.74***	8.84***
Fertilizer application	7.29***	6.47***	5.97***	5.01***	5.18***	6.09***	7.88***
Total power of agricultural machinery	0.16***	0.10***	0.32***	0.44***	0.36***	0.24***	0.26***
Likelihood logarithmic function value	−908.71	−904.58	−902.60	−912.88	−925.79	−933.68	−936.73
Spatial autoregressive coefficient	0.18	0.22	0.33	0.54	0.61	0.62	0.66

*$p < 0.1$, **$p < 0.05$, and ***$p < 001$.

factors indicate that these factors pass the significance test at the 1% probability level in all seven-time cross sections, showing a positive correlation. It shows that the level of grain production in the County region of Jiangsu Province is not only influenced by the production level of the region, but also by the neighboring regions.

The correlation between grain per capita and grain production showed a significant upward trend during 1990–2005, after which the correlation gradually decreased, but the change was not significant. The correlation between grain sown area and grain production showed a gradual upward trend during the past 30 years, indicating that grain sown area has a long-term, close and positive influence on grain production; The correlation between effective irrigated area and grain yield showed a significant downward trend during the period 1990–1995, and then gradually increased after 1995, and the increase in different periods is more consistent. The correlation between the number of agricultural population and grain yield had a small increase in 1990–1995, then a small decrease in 1995–2000, an annual increase in 2000–2015, and then a decrease in 2015–2020, with a generally limited range of fluctuation; The correlation between cropland area and cereal production was positively affected, with a small decrease in 2000 and a gradual increase after 1995, with a more consistent increase between time periods; The correlation between fertilizer application and grain yield shows a gradual downward trend between 1990 and 2015 and turns into an upward trend from 2015 to 2020, but the range of fluctuation is not large; The decrease in the likelihood logarithmic function value indicates that the ability of the statistical model to explain changes in grain yield gradually weakened during this period. The spatial autoregressive coefficient shows an increasing trend from 1990 to 2020. This suggests that the spatial dependence or interaction between adjacent regions has increased over time (Table 2).

4 Discussion

This study thoroughly analyzes the spatial and temporal changes of grain production in the counties of Jiangsu Province from 1990 to 2020, explores the trend of shifting the center of gravity of it, reveals the potential imbalance differences in grain production in the sustainable development of county cities, and identifies the key factors affecting this change. This analysis provides theoretical and empirical evidence to better optimize and improve the grain production system in the future.

Particularly in southern Jiangsu, rapid urbanization and industrialization have led to a reduction in arable land, which in turn has affected the region's grain production capacity. The rapid urbanization process is the most critical factor affecting regional grain production, which not only directly affects changes in arable land and agricultural production, but also indirectly affects grain production by influencing socio-economic factors, such as changes in demographic structure and economic patterns (Jha, 2019). To address this imbalance, it is necessary to pay more attention to the synergistic development of the intra-regional supply and demand system, make a comprehensive integration of socio-economic factors, and actively create an appropriate policy environment for grain production within and among regions, while coordinating the regional distribution of agricultural production conditions (Yin et al., 2021).

4.1 Regional differences in spatial and temporal patterns of grain production

In this study, per capita grain is used as a core indicator to measure the grain production situation of regions within Jiangsu Province. Per capita grain directly reflects the adequacy of food supply in a region. Different regions (e.g., northern Jiangsu and southern Jiangsu) have significantly different per capita grain, and these differences highlight the unevenness and diversity of grain production status among regions from the perspective of supply and demand balance. The grain production capacity in southern Jiangsu is limited by the urbanization process, in which land is converted to non-agricultural use (Jian-Sheng et al., 2013). This is consistent with the aforementioned reduction in cropland area and changes in fertilizer use, which may have reduced the region's agricultural production capacity and thus affected the per capita grain share (Li and Li, 2019). In contrast, despite the abundance of arable land resources in northern Jiangsu, its grain production potential has not been fully utilized due to problems with land management and utilization efficiency.

Exploring the spatial and temporal evolutionary patterns of grain production provides an important analytical framework for studies that seek to identify the main factors affecting grain production and contributes to a deeper understanding of grain production disparities between regions. This perspective not only emphasizes the importance of assessing the capacity of grain production within regions, but also highlights the challenges of adapting to the changing food needs of populations.

4.2 Impact of socio-economic factors on grain production

Socio-economic factors are important checks and balances to ensure grain production. By analyzing the relationship between per capita grain production and socio-economic factors, this study reveals the complexity of intra-regional grain production. These findings can help policymakers and relevant organizations to better consider interregional variability and specific needs when formulating grain production strategies.

In addition, as Jiangsu's economy grows and residents' incomes rise, the structure of food demand has changed. Residents' demand for high-quality and diversified food products has increased, especially in the more economically developed southern Jiangsu. However, this demand growth has not been supported by effective local grain production, reflecting the imbalance between supply and demand in different regions. Agricultural technology promotion, land management policies, etc., can increase grain production in a region and thus affect the per capita grain (Ladha et al., 2016). Per capita grain availability is closely related to socio-economic factors such as economic level, population structure, and urbanization (Liu et al., 2021b). Changes in these socio-economic factors are in turn reflected in changes in per capita grain availability, providing evidence that the grain production situation changes in response to socio-economic development. The encroachment of urbanization on arable land and the increasing "de-farming" and "de-fooding" of arable land, especially the reduction of high-quality farmland, have limited the region's grain production potential (Chunxia et al., 2020; Yusheng et al., 2023). The level of economic development in southern Jiangsu is higher than in northern Jiangsu, leading to greater demand for food and more urgent conflicts between supply and demand. To further promote the systematic development of the grain production system, it is necessary to explore the dynamics of the food supply and demand balance in the region and the driving factors behind it through in-depth research (Shen et al., 2023). As demographics and economic conditions change, so does the demand for food, and the balance of per capita grain supply and demand can help predict and prepare for these changes (Wang et al., 2022).

The processes of industrialization and urbanization have a dual impact on grain production. On the one hand, they provide an impetus for economic development and create more employment opportunities, thereby raising per capita income levels; on the other hand, industrialization and urbanization also take up a large amount of land that would otherwise be used for agricultural production (Tokula and Adekiya, 2018). The development of this imbalance is related to the rapid acceleration of urbanization in Jiangsu Province since the 1990's, which has led to a reduction in agricultural land, which in turn has affected the area sown to grain and production (Liu et al., 2019). The decrease in cultivated area and the change in the amount of fertilizer applied may reflect the pressure on agricultural land in the process of urbanization (Prasath and Navaneethan, 2022). In addition, the process of urbanization has led to a shift of labor from the agricultural to the non-agricultural sector, which may limit the development potential of agricultural production. Changes in the demographic structure of the population, especially the urban-rural ratio, also have an impact on grain production. As the population concentrates in urban areas, rural areas may face labor shortages, affecting the efficiency of agricultural production. At the same time, the aging of the population may also become a challenge for agricultural production, especially in areas with intensive agricultural labor (Lv et al., 2022). The economic construction of Jiangsu Province has provided sufficient financial and technical support to improve the quality and efficiency of food production. Capital investment can be used to purchase more advanced agricultural machinery, build modern agricultural facilities, and introduce high-yield and high-quality seeds and fertilizers. In terms of technical support, the promotion of advanced production methods, such as smart agriculture and precision agriculture, has improved the technological content and efficiency of food production and achieved a steady increase in output. Industrial upgrading has contributed to the optimization of the economic structure, which means for the grain industry that it needs to focus more on quality rather than just on output. With the rapid development of the processing and service industries, the grain industry chain has been extended, including the rise of grain processing and deep-processing industries, which has not only increased the added value of grain, but also contributed to the increase in farmers' income. At the same time, this also requires that food production must adapt to changes in market demand and focus on producing more diversified and higher-quality agricultural products. A comprehensive integration of the mechanisms by which socio-economic factors affect grain production is essential for formulating effective grain production strategies and promoting the sustainable development of regional agriculture (Jiang et al., 2021).

4.3 Impact of agricultural production conditions on grain production

Agricultural production conditions play a key role in the spatial and temporal variation of grain production in Jiangsu Province. This study examines how different agricultural production conditions affect the grain production situation in each region. Specifically, these conditions mainly include the utilization of agricultural resources and the application of agricultural technologies.

As the source region for the South-to-North Water Diversion Project, Jiangsu Province relies heavily on effective water resource management for grain production. Especially in northern Jiangsu, increasing the effective irrigated area will help ensure stable crop growth under unfavorable climatic conditions such as drought, and improving the irrigation system is particularly important for improving grain production, especially in response to the persistent "Extreme high temperatures" that have occurred in Jiangsu during the summer in recent years. The relationship between fertilizer application and grain production has increased in recent years, reflecting the fact that the Jiangsu government has consolidated the fragmentation of farmland in recent years to protect the "Red line of farmland," which has led to a significant increase in the efficiency of grain cultivation (Li et al., 2023). At the same time, with the vigorous implementation of the Jiangsu government's policy of "Two reductions" of chemical fertilizers and pesticides, the impact of the concept of agricultural sustainability has expanded, and "Reducing fertilization, increasing efficiency and increasing production" has gradually become the goal of fertilizer application in the new era. The comprehensive impact of improving the efficiency of fertilizer use on agricultural efficiency, environmental efficiency, and ecological efficiency (Wang et al., 2023). It should be noted that the excessive application of chemical fertilizers should be prevented in the excessive pursuit of production improvement. Under the traditional production-oriented planting mode, the excessive application of chemical fertilizers will lead to a high intensity of development of arable land resources, a decline in the quality of the soil environment, and a deterioration in the quality of food products. At the same time, in the wave of the nation's vigorous promotion of modern agriculture and intelligent agriculture, the progress of agricultural mechanization and technological upgrading are intertwined with other factors that have affected the grain production model (Lu and Huan, 2022; Zeng and Hu, 2023). Different regions in Jiangsu Province differ in terms of arable land area, land quality and land use efficiency. Arable land resources are scarce in southern Jiangsu, and it is urgent to improve the grain production efficiency per unit area of arable land, while further integrating the fragmented arable land and strengthening the promotion and demonstration of new intelligent agriculture (Liu et al., 2010). In contrast, although northern Jiangsu has more arable land resources, the efficiency of land management and use has become the key to improving production. Advances in agricultural technology, such as seed improvement, pest and disease management, soil water and fertilizer management, and agricultural mechanization, can effectively improve agricultural productivity and efficiency (Nkurunziza et al., 2020).

4.4 Impact of the policy environment on grain production

As Jiangsu Province is located on the "Qinling-Huaihe Line" in China (the demarcation line between the drylands in the north and the rice fields in the south), and as the core area of the Yangtze River Delta Economic Zone, its unique geographical location has led to the need for a region-specific policy environment to ensure grain production in the southern and northern parts of the province. Policymakers need to adopt different strategies when considering the differences in economic and agricultural capacity between regions. For example, agricultural policies in the highly industrialized southern Jiangsu should focus on protecting farmland and promoting modernization, while northern Jiangsu needs policy support to improve agricultural efficiency and productions. Policy differences between regions can also lead to uneven grain production capacity. For example, northern Jiangsu may benefit more from agricultural support policies because of its large arable land and many projects that can optimize and modernize the agricultural industry. Government support for agriculture, including subsidies, financial inputs, technical training, and infrastructure construction, can further ensure the stability of the food supply side. Market regulation and pricing policies are also important to balance supply and demand, stabilize markets, and protect farmers' interests. The government needs to ensure the price stability of agricultural products through optimized purchasing and marketing policies and scientific price subsidies (Lal, 2016). Just as in India, to ensure income stability for farmers, the government has set minimum support prices for key agricultural commodities, reducing risk for farmers and stabilizing grain production at the source (Morales et al., 2021).

Balancing grain production and consumption among regions is key to maintaining grain production. In the future, grain production and distribution strategies have to be adapted to demographic changes, especially in densely populated areas. Changes in food demand are taken into account in the formulation of economic policies to promote the synchronization of food supply and demand with economic development (Liu et al., 2023). Cooperation among regions and with external economic zones and large regions will be strengthened, and external resources and markets will be utilized to promote the stability of the internal food supply.

This study provides an important reference for the formulation of future food and agricultural policies. The development of food supply and the factors influencing it are different in different regions, and in order to promote the sustainability of grain production, policies should fully take into account local characteristics and develop differentiated grain production policies (Gatto et al., 2023). Future research can further consider more factors such as climate change, soil quality, agricultural policies, market changes, etc. (Chino, 2016; Hayek et al., 2020; Chen et al., 2023). This deepens understanding of the relationship between food supply and grain production. In addition, a finer spatial scale can be used to analyze in depth the pattern of grain production and the factors affecting it in different regions (Teeuwen et al., 2022).

Grain production in Jiangsu Province is characterized by a clear geographical distribution of "southern consumption and northern production" (Cao et al., 2023). This pattern is crucial to ensuring food security and economic development in the region and the country as a whole. In order to promote the rapid development of modern agriculture in southern Jiangsu and support the sustainable progress of agriculture in northern Jiangsu, we can start from various aspects and synergize with various strategies, including strengthening inter-regional agricultural cooperation (Viana et al., 2021), upgrading the level of modern agricultural technology

(Agriculture 4.0; Rose et al., 2021), optimizing the structure of the agricultural industry (Liu et al., 2021a), strengthening the construction of grain reserves and logistics systems (Ziegler et al., 2021), and implementing policy support and incentive measures (Viana et al., 2021). These initiatives will help to improve the overall level of agriculture in Jiangsu Province and ensure food security, and will require the joint efforts of the government, enterprises and farmers to form a synergy that promotes the sustained and healthy development of agriculture.

In 2024, the Chinese government's Central Document No. 1 called for the improvement of the "Trinity" protection system for the quantity, quality and ecology of arable land, the promotion of the construction and modernization of irrigation districts, as well as the scientific use of abandoned land and saline land. Jiangsu Province has also proposed to accelerate the whole process of mechanization and intelligent promotion actions, accelerate the construction of demonstration counties for the whole process of comprehensive mechanization of agricultural production, improve the quality and efficiency of agricultural machinery operations, vigorously develop regional agricultural machinery socialized services, and improve the level of intelligent and green agricultural machinery.

This study also proves the positive effects of effective irrigation area and total power of agricultural machinery on the sustainable production of grain. In the future, on the basis of improving the quality of arable land and vigorously developing modern agriculture, continuing to promote the key technology research and the integration and application of advanced and applicable technologies in accordance with local conditions will greatly promote the sustainable development of grain production in Jiangsu Province and even in the whole country.

5 Conclusion

Based on the extensive analysis of grain production in Jiangsu Province from 1990 to 2020, this study identifies significant regional disparities that have crucial implications for sustainable agricultural practices. While overall grain production has increased, southern Jiangsu faces a decline due to urbanization impacting arable land, contrasting with advancements in agricultural technology and resource management in northern and central Jiangsu that have spurred growth. This research underscores the necessity of tailoring future policies to regional specifics, advocating for the protection and optimization of arable land in the south and the enhancement of agricultural technologies in the north. An integrated approach considering socio-economic factors, agricultural conditions, and policy environments is essential for the sustainability of grain production and mitigating future risks.

Future research on the sustainable development of grain production should focus on further more potential imbalanced differences and promote grain production in an integrated manner at different scales and from the perspective of different factors, based on regional development positioning and resource endowments. There are still some shortcomings in this study, given the complexity and guidance of policy variables, the variables in the policy environment will also be a future research factor in this study; meanwhile, the high incidence of climate change in recent years has also had different degrees of impacts on food production, and the evolution of climate change and its driving force is also an important research direction.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

XiaL: Conceptualization, Methodology, Software, Writing – original draft, Writing – review & editing. JX: Conceptualization, Funding acquisition, Methodology, Writing – original draft. ZG: Investigation, Resources, Writing – original draft. XinL: Formal analysis, Writing – original draft. TJ: Project administration, Writing – original draft. JL: Data curation, Supervision, Writing – original draft. TL: Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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