Spatiotemporal Evolution and Driving Factors of Major Crop Production in Arid Regions: A Case Study of Xinjiang Region Postprint

Authors: Wang Fuhong, Xia Yong

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Abstract

Agriculture in arid regions, constrained by unique resource and environmental conditions, plays a crucial role in regional socioeconomic development and ecological civilization construction. Taking Xinjiang as an example, this study employs methods including the gravity center shift model, locational Gini coefficient, comparative advantage index, and global Moran' s I at the county scale to analyze the spatiotemporal evolution characteristics and influencing factors of production patterns for six major crop categories in Xinjiang from 2000 to 2020. The results indicate: (1) From 2000 to 2020, the scale of agricultural cultivation in Xinjiang continuously expanded, and a basic competitive pattern emerged among major crop productions characterized by the "advance" of cotton, vegetables, and melons and the "retreat" of grain, oil crops, and sugar crops. (2) The production gravity centers of the six major crop categories clustered in the central-western region, with the agglomeration degree of cotton, vegetable, and melon production continuously strengthening and production scale concentrating toward a few counties. (3) At the national level, Xinjiang' s major crop production all possesses efficiency comparative advantage, while cotton, sugar crops, and melons simultaneously enjoy scale comparative advantage and comprehensive comparative advantage, with cotton' s scale comparative advantage being particularly prominent. At the regional level, most counties in Xinjiang do not have comparative advantage in major crop production, and even for those counties with comparative advantage, it is primarily dominated by scale advantage. (4) Policy guidance, technological progress, and increased farmer income are important factors influencing the evolution of regional major crop production patterns.

Full Text

Spatio-temporal Pattern Evolution and Influencing Factors of Main Crops Production in Arid Regions: A Case Study of Xinjiang

WANG Fuhong[1,2], **XIA Yong**[2]

[1]School of Agriculture and Forestry Economics and Management, Lanzhou University of Finance and Economics, Lanzhou 730101, Gansu, China
[2]College of Economics and Management, Xinjiang Agricultural University, Urumqi 830052, Xinjiang, China

Abstract

Agriculture in arid regions plays a vital role in regional socioeconomic development and ecological civilization construction due to unique resource and environmental constraints. Taking Xinjiang as a case study, this paper employs the center of gravity transfer model, locational Gini coefficient, comparative advantage index, and global Moran' s I index at the county scale to analyze the spatio-temporal evolution characteristics and influencing factors of six major crops from 2000 to 2020. The results indicate that: (1) Xinjiang' s agricultural planting scale expanded continuously during 2000–2020, with a fundamental competitive pattern emerging where cotton, vegetables, and melons "advanced" while grain, oil, and sugar crops "retreated." (2) The production centers of the six major crops concentrated in the central-western region, with the agglomeration degree of cotton, vegetable, and melon production continuously strengthening and production scale concentrating in fewer counties. (3) At the national level, Xinjiang' s major crop production all exhibited efficiency comparative advantages. Cotton, sugar, and melon production demonstrated both scale and comprehensive comparative advantages, with cotton' s scale advantage being particularly prominent. At the regional level, most counties in Xinjiang lacked comparative advantages in major crop production, and those with advantages were primarily scale-dominated. (4) Policy guidance, technological progress, and increased farmer income represent important factors influencing the evolution of regional crop production patterns.

Keywords: crops; spatio-temporal pattern; comparative advantage; arid region; Xinjiang

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Introduction

As a foundational industry of the national economy, agriculture provides essential nutrients and energy for human survival and development, as well as the necessary material basis for sustained socioeconomic progress. However, China's agricultural production foundation remains fragile due to climate change, geopolitical conflicts, trade friction, and shifts in residents' food consumption structures, increasing uncertainty and necessitating transformation and upgrading. Meanwhile, Xinjiang' s cultivated land has shown an increasing trend against the national backdrop of reduction, profoundly altering China' s agricultural production pattern and influencing regional socioeconomic development and national supply of important agricultural products. Leveraging its unique resource endowments, Xinjiang produced 90.19% of the nation' s cotton, 44.68% of sugar crops, 15.41% of melons, and 2.64% of grain in 2020. However, as an underdeveloped region constrained by water scarcity, fragile ecological environments, and weak economic foundations, Xinjiang' s agricultural production efficiency requires improvement. There is an urgent need to deepen understanding of the spatio-temporal evolution characteristics and formation mechanisms of regional crop production patterns to optimize agricultural layout and enhance comprehensive benefits during scale expansion.

Crop production structure and layout constitute important components of agricultural development and key research topics in agricultural geography and sustainable agricultural development. Recent studies have examined agricultural production spatial evolution and safety evaluation at national and provincial scales, while production layouts of single crops such as grain, soybeans, and maize have also received widespread attention. Although existing research provides a solid foundation for understanding crop production pattern evolution, several gaps remain. Notably, studies on comparative advantages in ecologically fragile arid regions are relatively weak. Current research on Xinjiang' s crop production patterns and comparative advantages primarily focuses on single crops, lacking a holistic understanding of competitive dynamics, evolution characteristics, and driving mechanisms across different crops. As optimization goals for crop planting structures shift from pursuing economic benefits to comprehensive benefits emphasizing harmonious human-land relationships, deepening understanding of crop production pattern evolution in arid regions is crucial for optimizing agricultural layout and tapping production potential. Based on this context, this paper employs the county as the research unit and uses the center of gravity transfer model, locational Gini coefficient, and other methods to analyze the spatio-temporal evolution characteristics and influencing factors of Xinjiang' s major crop production from 2000 to 2020, aiming to provide decision-making references for regional agricultural economic development.

1.1 Study Area Overview

Xinjiang is located in northwestern inland China (73°25 -96°24 E, 34°09 -49°08 N), covering a total area of 1.66$\times10^{6}$ km^2, approximately one-sixth of China' s territory. The region features a typical arid climate with scarce precipitation (average annual precipitation of 146.4 mm) and high evaporation (1,600–2,300 mm). Despite water scarcity for agricultural development, Xinjiang possesses superior combinations of light, heat, and land resources.

In 2020, Xinjiang' s crop planting area reached 6.28×10^{6} hm^2, with agricultural output value of 2.94×10^{11} yuan.

1.2 Data Sources

Considering Xinjiang' s crop production characteristics and data availability, this study selected grain, cotton, oil crops, sugar crops, vegetables, and melons as research objects. Based on Xinjiang' s administrative divisions and data characteristics, administrative changes during 2000–2020 were corrected, and municipal districts under the same prefecture-level city were merged into single research units, yielding 98 basic county-level research units. Data were primarily sourced from the *Xinjiang Statistical Yearbook* and *Xinjiang Production and Construction Corps Statistical Yearbook* (2001–2021).

1.3 Theoretical Analysis

Crop production is a natural-economic complex open system influenced by multiple factors including water, soil, climate, labor, technology, markets, and policy, giving agriculture dual characteristics of natural and economic reproduction. Consequently, crop production pattern formation and evolution are inevitably affected by natural environments, economic development, technological progress, and national policy. China' s vast territory exhibits significant regional differences in agricultural production factors. Existing crop production patterns cannot meet local or overall agricultural development needs during climate change and rapid socioeconomic development, nor do they facilitate efficient agricultural resource allocation and overall social benefit improvement. With the injection of new elements such as policy guidance and market inducement, crop production patterns change to achieve maximum benefits.

Natural resource endowments form the foundation of crop production pattern evolution. Light-heat conditions, topography, and irrigation water sources determine the suitability and spatial distribution possibilities of different crops. The formation of advantageous and characteristic agricultural industrial clusters such as Xinjiang cotton and Gansu potatoes is primarily based on local unique natural resource endowments, forming basic distribution patterns through intergenerational transmission of planting practices. Market economic factors constitute the internal driving force of crop production pattern evolution. The economic attributes of agricultural production determine that farmers' crop selection is driven by expected economic returns. Declining maize planting profits and rising soybean profits have led to expanding soybean cultivation in traditional maize concentration areas such as Heilongjiang, Jilin, and Inner Mongolia.

Technological progress creates favorable conditions for crop production pattern changes. Agricultural technological advances break through constraints of certain natural factors, expanding agricultural production geographical ranges and crop distribution suitability, while empowering traditional agricultural production factors and strengthening crop production spatial patterns. Policy planning ensures maximum benefits of crop production pattern evolution. Agricultural products possess quasi-public goods attributes and are crucial for ensuring people' s livelihoods and social stability. Due to the blindness of market mechanisms, farmers' spontaneous adjustment of crop planting structures cannot maximize socio-economic-ecological benefits. Therefore, effective macro-control must guide and modify economically rational crop production patterns. Cotton target price subsidy policies have enhanced Xinjiang cotton industry' s competitiveness, forming a national production pattern where Xinjiang cotton "stands out."

1.4 Research Methods

1.4.1 Center of Gravity Transfer Model Following Yang et al. [20], this study employs the gravity transfer model to simulate production center coordinates and movement distances of Xinjiang' s major crops in different years. The specific formulas are:

$$X_j = \frac{\sum_i M_{ij} \times X_i}{\sum_i M_{ij}}$$

$$Y_j = \frac{\sum_i M_{ij} \times Y_i}{\sum_i M_{ij}}$$

where X_j and Y_j represent the center coordinates of crop j' s production; M_{ij} is the yield of crop j in unit i (10^4 t); and X_i and Y_i are the geometric center coordinates of unit i.

The center movement distance formula is:

$$d_{\alpha\beta} = k \times \sqrt{(X_\alpha - X_\beta)^2 + (Y_\alpha - Y_\beta)^2}$$

where $d_{\alpha\beta}$ is the movement distance of the center from year α to year β (km); k is a constant (111.111 km); and (X_α, Y_α) and (X_β, Y_β) are the center coordinates of crop yield in years α and β, respectively.

1.4.2 Locational Gini Coefficient Following Zhang [27], this study uses the locational Gini coefficient to characterize the uneven degree of crop spatial production distribution, with higher values indicating greater spatial concentration. The calculation formula is:

$$G_j = 1 - \frac{1}{n}\sum_{q=1}^{n}(R_{qj} + 1 - R_{q-1,j})$$

where G_j is the locational Gini coefficient of crop j; n is the number of groups after sorting county units by crop j' s yield from low to high and dividing them equally. This study divides 98 counties into 10 groups, i.e., $n = 10$; R_{qj} is the cumulative percentage of crop j' s yield in group q relative to the total yield of crop j across all counties.

1.4.3 Comparative Advantage Index This study adopts scale comparative advantage index, efficiency comparative advantage index, and comprehensive comparative advantage index [28] to measure regional crop production comparative advantages under the combined influence of natural endowments and economic factors.

The scale comparative advantage index represents the scale advantage of a specific crop in a region, calculated as:

$$SAI_{ij} = \frac{S_{ij}/S_i}{S_j/S}$$

where SAI_{ij} is the scale comparative advantage index of crop j in unit i; S_{ij} is the planting area of crop j in unit i (10^3 hm^2); S_i is the total crop planting area in unit i (10^3 hm^2); S_j is the planting area of crop j in the higher-level region (10^3 hm^2); and S is the total crop planting area in the higher-level region (10^3 hm^2).

The efficiency comparative advantage index represents production efficiency advantages, calculated as:

$$EAI_{ij} = \frac{P_{ij}}{P_j}$$

where EAI_{ij} is the efficiency comparative advantage index of crop j in unit i; P_{ij} is the unit area yield of crop j in unit i ($kg \cdot hm^{-2}$); and P_j is the unit area yield of crop j in the higher-level region ($kg \cdot hm^{-2}$). $EAI > 1$ indicates that the region has higher production efficiency than the higher-level region, with larger values indicating greater advantages; $EAI < 1$ indicates no efficiency advantage.

The comprehensive comparative advantage index fully characterizes the overall comparative advantage level:

$$AAI_{ij} = \sqrt{SAI_{ij} \times EAI_{ij}}$$

where AAI_{ij} is the comprehensive comparative advantage index of crop j in unit i. $AAI > 1$ indicates comprehensive comparative advantage, with larger values showing more prominent advantages; $AAI < 1$ indicates no comprehensive advantage. Following Tu et al. [28], counties are classified into two primary zones (advantage and disadvantage zones) and six secondary zones (balanced advantage, scale-dominated advantage, efficiency-dominated advantage, low-scale disadvantage, low-efficiency disadvantage, and absolute disadvantage zones).

1.4.4 Global Moran' s I Index Given spatial autocorrelation among variables, this study employs the global Moran' s I index to characterize whether scale, efficiency, and comprehensive comparative advantages of Xinjiang's major crops exhibit agglomeration effects. The formula is:

$$I = \frac{n}{\sum_i \sum_y w_{iy}} \times \frac{\sum_i \sum_y w_{iy}(x_i - \bar{x})(x_y - \bar{x})}{\sum_i (x_i - \bar{x})^2}$$

where I is the global Moran' s I index ranging from $[-1, 1]$; n is the number of spatial units; x_i and x_y are comparative advantage indices of units i and y; $\bar{x}$ is the mean comparative advantage index; and w_{iy} is the spatial weight matrix.

2 Results and Analysis

2.1 Temporal Variation Characteristics of Crop Planting Scale in Xinjiang

Xinjiang' s crop planting scale showed continuous expansion from 2000 to 2020, with grain and cotton as the main crops. Grain, oil, sugar, vegetable, and melon planting areas increased by 51.88%, 147.13%, 153.03%, 108.00%, and 42.85%, respectively, while cotton planting area decreased by 42.85%. Grain and cotton showed the highest net increases: grain increased by 76.18$×10^{4}$ hm^2 and cotton by 148.95$×10^{4}$ hm^2. The variation coefficients of planting area for grain, cotton, oil, sugar, vegetables, and melons were 0.15, 0.44, 0.16, 0.44, 0.11, and 0.14, respectively, with cotton and sugar crops showing the greatest fluctuations.

As shown in [Figure 2: see original paper], total grain and vegetable yields showed fluctuating growth trends; cotton yield continued increasing with an average annual growth rate of 11.62%; oil crop yield remained relatively stable; sugar and melon yields experienced substantial fluctuations. The variation coefficients of yield for grain, cotton, oil, sugar, vegetables, and melons were 0.15, 0.44, 0.16, 0.44, 0.11, and 0.14, respectively, with melons showing the greatest fluctuation. Overall, Xinjiang' s major crop production formed a basic competitive pattern of cotton, vegetables, and melons "advancing" while grain, oil, and sugar crops "retreated."

2.2 Spatial Pattern Evolution of Major Crop Production in Xinjiang

Using ArcGIS 10.8, this study calculated the center coordinates and movement distances of major crop yields from 2000 to 2020 () and mapped their migration trajectories ([Figure 3: see original paper]). Overall, Xinjiang' s major crop production centers concentrated in the central-western region. Grain, oil, and cotton production showed a "northward" trend, while vegetable and sugar crop production showed a "southward" trend. Melon production exhibited opposite trends before and after 2010.

Grain and sugar crop production centers showed relatively small migration distances. The grain production center was located in Baicheng County in 2000, then moved northward and westward along a "Z"-shaped trajectory. Cotton and oil crop production centers showed larger migration distances, moving rapidly northward after 2010, indicating increased production contributions from northern Xinjiang. The vegetable production center moved continuously southward. The melon production center showed the largest movement, shifting rapidly southwestward before 2010, then northeastward afterward. These rebound characteristics likely result from significant farmland expansion and long-term overexploitation of water resources, prompting policies to reduce cultivated land and water use to coordinate socioeconomic development with resource-environment constraints, causing some crop production centers to rebound.

2.3 Comparative Advantage Analysis of Major Crop Production in Xinjiang

Xinjiang's major crop production demonstrated clear comparative advantages at the national level. As shown in [Figure 5: see original paper], from 2000 to 2020, Xinjiang' s scale comparative advantage indices for grain and vegetables were less than 1, while those for cotton, sugar, and melons exceeded 1. Cotton' s scale comparative advantage index increased, reaching a maximum of 5.21, indicating Xinjiang' s significant national scale advantage in cotton production. Except for melons and oil crops in individual years, efficiency comparative advantage indices for Xinjiang' s major crops all exceeded 1, indicating higher production efficiency than national averages. Comprehensive comparative advantage indices ranged 3.45–4.82 for cotton, 1.02–1.47 for sugar, and 3.12–5.21 for melons, all exceeding 1, demonstrating strong national competitive advantages.

The locational Gini coefficients for grain, cotton, and melons continuously increased, while those for vegetables and sugar crops decreased ([Figure 4: see original paper]), indicating that grain, cotton, and melon production became more concentrated in fewer counties, while vegetable and sugar crop production became more dispersed. Oil crops showed substantial fluctuations but overall agglomeration tendency.

To further analyze spatial characteristics of comparative advantages, this study used the global Moran' s I index. As shown in , except for efficiency comparative advantages of a few crops in individual years, the global Moran' s I indices for scale, efficiency, and comprehensive comparative advantages all exceeded 0, indicating significant spatial agglomeration—counties with higher comparative advantages tended to cluster together. However, the indices were generally not high, suggesting that while agglomeration exists, its degree is limited due to significant water resource constraints and mismatched land-water resources in Xinjiang, restricting spatial clustering and regional linkage effects.

To visualize comparative advantages at the county level, this study mapped advantage zones for 2020 ([Figure 6: see original paper]) and classified them based on [Figure 7: see original paper]. At the regional level, most Xinjiang counties lacked comparative advantages, with many being absolute disadvantage zones having neither scale nor efficiency advantages. Advantageous counties were primarily scale-dominated or balanced advantage zones, reflecting the unique "water determines land, water determines grain" characteristic of arid region agriculture, where irrigation conditions directly determine production scale and efficiency.

2.4 Influencing Factors of Crop Production Pattern in Xinjiang

Crop production involves both natural and economic reproduction, making planting structure and spatial layout susceptible to national policy, technological conditions, economic benefits, resource endowments, and other factors [14,27]. Based on theoretical analysis and related research [9,19-20], this study selected 8 indicators closely related to crop production pattern evolution as independent variables: rural per capita income, urbanization rate, cultivated land area, agricultural water use, agricultural expenditure as a proportion of fiscal expenditure, primary industry contribution rate, total agricultural machinery power, and freight turnover. Dependent variables comprised scale, efficiency, and comprehensive comparative advantage indices for different crops. Given multicollinearity among socioeconomic factors that affects modeling accuracy, this study employed partial least squares regression following related research [29], processing data using SIMCA-P software.

Model effects and variable importance reflect the influence strength of independent variables on dependent variables. As shown in , the primary factor affecting Xinjiang' s crop scale comparative advantage pattern is agricultural expenditure as a proportion of fiscal expenditure, reflecting that policy guidance is crucial for forming scale advantages. The *Plan for Supporting Xinjiang' s Agricultural and Animal Husbandry Development (2017-2020)* explicitly proposed goals of "securing grain, adjusting cotton, developing fruits, and promoting livestock," aiming to strengthen characteristic industries and build national bases for grain security reserve, high-quality commercial cotton, and characteristic forestry and fruit industries. Xinjiang' s agricultural production capacity has continuously improved over the past two decades, with cotton and melon industries strengthening, closely related to national policy support.

The main factor influencing efficiency comparative advantage pattern evolution is total agricultural machinery power, indicating that technological progress is key to improving production efficiency. Technology leadership and equipment support are important markers of modern agriculture. Taking water-saving irrigation technology as an example, regional water resource carrying capacity constrains oasis agriculture development [30]. As a typical oasis irrigation agriculture area in arid regions, improving water use efficiency is essential for ensuring Xinjiang' s agricultural production. According to the *China Water Resources Statistical Yearbook*, Xinjiang has continuously increased investment in agricultural water conservancy, implementing efficient water-saving construction. Water-saving irrigation area increased from 298.26×10^{3} hm^2 to 433.33×10^{3} hm^2, with micro-irrigation (drip and seepage irrigation) increasing by 135.53%.

Technological progress and farmer income changes most significantly influenced comprehensive comparative advantage pattern evolution (). Xinjiang' s mismatched land and water resources mean that agricultural technological progress can better optimize production factor allocation and improve resource use efficiency. Increased farmer planting income enhances demonstration effects of characteristic advantageous industries, promoting spillover of planting scope and technical experience, thereby driving industries into a cycle of cumulative self-reinforcement that enhances comprehensive advantages.

3 Discussion

Spatio-temporal evolution information of crop planting structure constitutes important foundational data for agricultural geography and sustainable development research, holding significant meaning for scientific agricultural management and food security early warning assessment. Agricultural production pattern evolution manifests both in inter-regional yield differences and in spatial allocation differentiation. Compared with existing research, this study focuses on arid region crop production pattern evolution, which shows opposite trends to national cultivated land changes. Its comparative advantages also differ significantly from other regions [8-9,13], particularly Xinjiang' s prominent scale comparative advantages in grain, cotton, and melon production. Xinjiang has become an important national production base for grain and cotton, prompting the adjustment of its grain policy from "regional balance with slight surplus" to "regional surplus for national supply" in 2020.

Government regulation, market inducement, and technological progress are crucial for crop production pattern and comparative advantage evolution [8-9,13]. Xinjiang' s competitive pattern of cotton, vegetables, and melons "advancing" while grain, oil, and sugar crops "retreat" reflects, against resource-environment constraints, how top-down macro-control and bottom-up market behaviors drive factor flows (labor, technology, capital, land), breaking original production paths under planting conventions and altering production structure and regional layout. Although some Xinjiang crops show significant comparative advantages, most counties at the regional level exhibit absolute disadvantage without scale or efficiency advantages, while advantageous counties are mostly scale-dominated. This stems from Xinjiang' s status as an underdeveloped region with significant unbalanced and insufficient development, coupled with water scarcity and fragile ecology that limit agricultural development and industrial benefits. Future development should optimize agricultural water resource allocation, improve rainfed agriculture water efficiency, upgrade agricultural infrastructure, innovate production and management models, and transform regional scale advantages into efficiency and comprehensive advantages to achieve optimal socio-economic-ecological benefits.

4 Conclusions

This study analyzed the spatio-temporal evolution and influencing factors of Xinjiang' s major crop production from 2000 to 2020, yielding four main conclusions:

(1) Xinjiang' s crop production scale expanded continuously from 2000 to 2020, dominated by grain and cotton. A fundamental competitive pattern emerged where cotton, vegetables, and melons "advanced" while grain, oil, and sugar crops "retreated."

(2) Production centers of the six major crops concentrated in the central-western region with varying degrees of displacement. Grain, cotton, and melon production showed increasing agglomeration, concentrating in fewer counties, while vegetable and sugar crop production became more dispersed. Oil crop production also showed agglomeration tendencies.

(3) At the national level, Xinjiang' s cotton, sugar, and melon production demonstrated scale comparative advantages, particularly pronounced for cotton. All major crops showed efficiency comparative advantages, with cotton, sugar, and melon production also possessing comprehensive comparative advantages. At the regional level, comparative advantage distribution was uneven across counties, with most being disadvantage zones and advantageous counties primarily scale-dominated.

(4) Policy guidance was the primary factor driving scale comparative advantage pattern evolution, technological progress was the main factor influencing efficiency comparative advantage pattern evolution, and both technological progress and farmer income increases significantly affected comprehensive comparative advantage pattern evolution.

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Note: Figure translations are in progress. See original paper for figures.