

Coupling Coordination and Spatiotemporal Variations between Water Resources and Agricultural Cropping Systems in Xinjiang: A Case Study of Grain and Cotton Cropping Systems (Postprint)

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Abstract

Abstract: To investigate the coupling coordination and spatiotemporal heterogeneity between water resources conditions and agricultural planting development in Xinjiang, this study takes the grain and cotton planting systems in Xinjiang as examples and, based on water resources and agricultural planting data from 14 prefectures during 2005–2019, employs the entropy method, coupling coordination degree model, and exploratory spatial data analysis to measure and analyze the comprehensive development indices of the water resources system and agricultural planting system, as well as the coupling coordination degree and spatiotemporal evolution patterns of the water resources-agricultural planting composite system (hereinafter referred to as the ‘composite system’). The results show that: (1) The comprehensive development index of Xinjiang’s composite system exhibits a spatial pattern characterized by ‘high in the central axis and low in the wings’, wherein the water resources system maintains a relatively high overall level, while the agricultural planting system demonstrates a faster growth trend. (2) The coupling coordination level of Xinjiang’s composite system generally displays a development trend of ‘high in the north and low in the south, but with gradually narrowing gaps’, and due to regional disparities, the agricultural planting system has gradually become a constraint hindering the coordinated development of the composite system. (3) The coupling coordination degree of Xinjiang’s composite system exhibits significant spatial agglomeration characteristics, yet its positive correlation shows a weakening trend from strong to weak. The research findings possess theoretical and practical significance for the sustainable utilization of water resources and the sound coordinated development of the agricultural planting system industry in Xinjiang.

Full Text

Preamble

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Coupling Coordination and Spatiotemporal Differences Between Water Resources and Agricultural Planting Systems in Xinjiang: A Case Study of Grain and Cotton Planting Systems

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Abstract: To investigate the coupling coordination and spatiotemporal differences between water resources and agricultural planting development in Xinjiang, this study examines grain and cotton planting systems as examples. Based on water resource and agricultural planting data from 14 prefectures in Xinjiang from 2005 to 2019, we employ the entropy method, coupling coordination degree model, and exploratory spatial data analysis to calculate the comprehensive development indices of water resource systems, agricultural planting systems, and the water resources-agriculture planting composite system (hereinafter “composite system”), and to analyze its coupling coordination degree and spatiotemporal evolution patterns. Results show: (1) The composite system’s comprehensive development index exhibits a spatial pattern of “high in the central axis and low on both wings,” with the water resource system maintaining a relatively high overall level while the agricultural planting system demonstrates a faster growth trend. (2) The coupling coordination level of Xinjiang’s composite system shows a “north-high, south-low” pattern, though this gap is gradually narrowing. Regional differences have caused the agricultural planting system to become a bottleneck hindering the coordinated development of the composite system. (3) The coupling coordination degree of Xinjiang’s composite system displays significant spatial clustering characteristics, though its positive correlation shows a weakening trend from strong to weak. These findings provide theoretical and practical guidance for the sustainable utilization of water resources and the coordinated development of agricultural planting systems in Xinjiang.

Keywords: water resources-agriculture planting composite system; coupling coordination degree; exploratory spatial data analysis; spatiotemporal differences; Xinjiang

1. Introduction

Xinjiang serves as a major reserve area for agricultural planting in China. The planting area, total output, and per-unit yield of its advantageous agricultural industries such as grain and cotton have shown a “three increases” trend, providing fundamental support for China’s agricultural self-sufficiency, food security, and economic stability. As a basic element supporting agricultural industries, water resources’ utilization structure and management methods continuously adjust with changes in crop planting structure and area. The supply, demand, and utilization efficiency of water resources are closely related to agricultural planting structure and modernization levels. Different crops have varying growth cycles and conditions, leading to different periodic water demand characteristics. Maintaining a balance between sustainable water resource utilization and crop planting benefits is crucial for stable agricultural production and livelihoods, especially in arid regions. Regarding crop-specific differences, Lang et al. [?] simulated water consumption of different crops during their growth cycles in arid regions. Jin [?] studied the impact of grain crop planting structure adjustments on water resource consumption. Zhang et al. [?] estimated the proportion of water footprint in cotton and other crop production in Northwest China and proposed regional water use regulation policies for cash crops.

In terms of effective water resource utilization and agricultural planting relationships, Wu et al. [?] noted that improving agricultural water use efficiency is essential for ensuring food security. Fang et al. [?] explored changes in water resource utilization value from a virtual water perspective after altering crop planting layouts. Xu et al. [?] proposed that in arid regions, the adoption of water-saving irrigation technologies should avoid affecting sustainable water resource utilization due to expanded planting scales. Sun et al. [?] pointed out that agricultural information technology construction plays an important role in reducing the water footprint intensity of grain and cotton. Yang [?] suggested that constructing water-saving incentive mechanisms for agricultural water resources under the rural revitalization strategy should start from the perspective of planting structure.

In summary, existing research on the relationship between water resources and individual crop planting industries is abundant, but few studies evaluate the coupling and coordinated development of water resources and agricultural planting systems, which could help measure the quantitative distance and development balance point for improving agricultural industrial structure adaptability to water resources. Luo et al. [?] explored the synergistic development trend of the water-food composite system in the Yellow River Basin, clarifying the constraints and importance of water resources in composite systems. Li et al. [?] similarly applied coupling coordination methods to enrich research on composite system coupling coordination in arid regions from perspectives such as ecological environment and tourism development.

With China’s proposed high-quality development goals for agricultural indus-

tries, the coupling coordination of Xinjiang's composite system requires in-depth consideration to fully leverage Xinjiang's resource endowment advantages and explore regional agricultural development differences. Based on data from 2005 to 2019 on water resources and agricultural planting development in Xinjiang, using grain and cotton planting as examples, this study employs coupling coordination degree models and exploratory spatial data analysis to examine the temporal evolution patterns and spatial clustering characteristics of composite system coupling coordination. This provides important theoretical references for the sustainable utilization of water resources and the benign coordinated development of agricultural planting system industries in Xinjiang.

2. Data and Methods

2.1 Indicator Selection and Data Sources

Generally, to measure the coupling coordination of regional water resource systems and agricultural industry systems, it is first necessary to evaluate the comprehensive development level (index) of the two subsystems to judge their basic development trends and determine the coupling coordination degree of the composite system. Xinjiang is an arid and water-scarce region where composite systems have dynamic coupling relationships [?], and water resources are essential basic elements for maintaining agricultural product planting industries. Agricultural water-saving irrigation technologies are particularly important for agricultural output. Additionally, water quantity and quality issues generated during agricultural planting processes pose obstacles to effective water resource development and sustainable utilization.

Based on the coupling relationship of composite systems and Xinjiang's water resource characteristics, and following principles of scientificity, systematicity, and data availability, this study constructs a coupling coordination comprehensive evaluation index system (Table) by combining relevant literature [?, ?, ?, ?, ?, ?, ?]. Using water resource and agriculture-related data from 14 prefectures in Xinjiang from 2005 to 2019, all data were obtained from the *Xinjiang Statistical Yearbook* for each year. Only a few missing data points were estimated through fitting historical values, such as domestic water consumption proportion and effective irrigation area in 2019. Most data could be directly obtained from or calculated based on the statistical yearbook. In the comprehensive evaluation index system, larger positive attributes or smaller negative attributes are more beneficial to composite system development.

2.2 Methods

2.2.1 Entropy Method Among various weight determination methods, the entropy method has broad applicability. Following reference [?], this method was used to determine indicator weights. First, the extremum method was employed to eliminate dimensional differences among indicators.

For positive indicators:

$$rt_{ij} = \frac{x_{tij} - \min(x_j)}{\max(x_j) - \min(x_j)}$$

For negative indicators:

$$rt_{ij} = \frac{\max(x_j) - x_{tij}}{\max(x_j) - \min(x_j)}$$

where rt_{ij} is the dimensionless value of indicator j in region i in year t , with $rt_{ij} \in [0, 1]$; $\max(x_j)$ and $\min(x_j)$ are the maximum and minimum values of indicator j , respectively.

Second, the information entropy (e_j) of each indicator is calculated, and the entropy weight (w_j) is derived from the information entropy.

$$e_j = -\theta \sum_{t=1}^{\theta} \sum_{i=1}^m p_{tij} \ln(p_{tij})$$

where θ is the total number of years; m is the total number of regions; n is the number of indicators; the constant $\theta = 1/\ln(\theta \times m)$; and $p_{tij} = rt_{ij} / \sum_{t=1}^{\theta} \sum_{i=1}^m rt_{ij}$.

The entropy weight is then calculated as:

$$w_j = \frac{1 - e_j}{\sum_{j=1}^n (1 - e_j)}$$

2.2.2 Comprehensive Development Index The comprehensive development indices for water resources (T_w), agricultural planting (T_a), and the composite system (T) are calculated from the standardized values and weights of the indicators.

$$T_i = \sum_{j=1}^n w_j \cdot rt_{ij}$$

where T_i is the comprehensive development index of a subsystem; λ and μ represent the importance of water resources and agricultural planting systems to regional development, respectively. Since both subsystems are equally important, we set $\lambda = \mu = 0.5$.

2.2.3 Coupling Coordination Degree Model The term “coupling” originates from physics, describing the phenomenon of mutual influence between different systems. “Coupling coordination” extends this concept, representing the harmonious and orderly development of different systems and emphasizing benign interactions. The coupling coordination degree measures this benign interaction [?]. The coupling coordination degree of the composite system reflects the coupling coordination state between water resources and agricultural planting subsystems, constructed as follows:

$$C = 2\sqrt{\frac{T_w \times T_a}{(T_w + T_a)^2}}$$

$$D = \sqrt{C \times T}$$

where C is the coupling degree; D is the coupling coordination degree with a value range of $[0, 1]$; and T is the composite system’s comprehensive development index.

Based on the coupling coordination degree value, the coordinated adaptation stage of the composite system can be determined (Table).

2.2.4 Exploratory Spatial Data Analysis Exploratory spatial data analysis can identify data clustering or random distribution patterns [?]. This study employs global and local spatial autocorrelation methods to empirically test the spatial correlation and clustering degree of coupling coordination degrees across Xinjiang’s 14 prefectures.

Global spatial autocorrelation is commonly measured using the global Moran’s I:

$$\text{Moran's I} = \frac{\sum_{i=1}^m \sum_{k=1}^m w_{ik} (x_i - \bar{x})(x_k - \bar{x})}{\sum_{i=1}^m \sum_{k=1}^m w_{ik} \sum_{i=1}^m (x_i - \bar{x})^2}$$

where x_i and x_k are attribute values of regions i and k ; \bar{x} is the sample mean; and w_{ik} is the spatial weight representing the degree of mutual influence between regions.

Local spatial autocorrelation is generally analyzed using local Moran’s I and LISA clustering maps. The Moran scatter plot has four quadrants: the first (third) quadrant represents “high-high” (“low-low”) clustering, indicating positive spatial correlation where high (low) values cluster together; the second and fourth quadrants represent “low-high” and “high-low” clustering, respectively, indicating negative spatial correlation.

The local Moran’s I (I_i) is calculated as:

$$I_i = \frac{(x_i - \bar{x}) \sum_{k=1}^m w_{ik}(x_k - \bar{x})}{\sum_{i=1}^m (x_i - \bar{x})^2}$$

Regarding the setting of w_{ik} in equation (6), this study uses the common inverse distance weight:

$$w_{ik} = \frac{1}{d_{ik}}$$

where d_{ik} is the spatial distance between regions i and k .

3. Results

3.1 Comprehensive Development Index Analysis

3.1.1 Water Resources and Agricultural Planting System Comprehensive Development Indices Xinjiang's water resource system comprehensive development index shows temporal differences but the gap is gradually narrowing, and a spatial characteristic of "high in the north, low in the south." The water resource system in northern Xinjiang has developed relatively slowly overall, with the comprehensive development index increasing from 0.387 in 2005 to 0.436 in 2019, a growth rate of 12.71%. However, Karamay City and Urumqi City in northern Xinjiang have consistently ranked at the forefront of Xinjiang during the study period. The water resource system comprehensive development index in southern Xinjiang increased from 0.187 to 0.247, with a growth rate of 32.07%. Although Hotan Prefecture and Kashgar Prefecture showed the largest increases at 52.68% and 54.19% respectively, they remained below the overall average. Turpan City and Aksu Prefecture have long ranked at the bottom in Xinjiang.

Additionally, Xinjiang's agricultural planting system comprehensive development index has a relatively low mean value but a fast growth trend, increasing from 0.188 in 2005 to 0.248 in 2019, a growth rate of 31.95%. Overall differences in the agricultural planting system comprehensive development index are small, but inter-prefecture differences are large, with extreme value differences around 0.3. Northern and southern Xinjiang agricultural planting systems show different development characteristics (Figure [Figure 2: see original paper]). Karamay City and Ili Prefecture Directly-administered Counties are the best-performing regions in Xinjiang's agricultural planting system, with comprehensive development indices exceeding 0.4 in 2019. These two regions also showed the highest growth rates. In contrast, Kizilsu Kirghiz Autonomous Prefecture (Kizilsu), Turpan City, and Hami City have poor agricultural planting system development, with indices below 0.15 and the lowest growth rates.

3.1.2 Composite System Comprehensive Development Index Xinjiang's composite system comprehensive development index increased from 0.288 in 2005 to 0.359 in 2019, a growth rate of 24.64%. The composite system comprehensive development indices of various prefectures can be roughly divided into three tiers (Figure [Figure 3: see original paper]). Ili Prefecture Directly-administered Counties, Karamay City, and Bayingolin Mongol Autonomous Prefecture (Bayingolin) form the first tier with the best comprehensive development status, far exceeding other prefectures. Urumqi City, Tacheng Prefecture, Changji Hui Autonomous Prefecture (Changji), and Bortala Mongol Autonomous Prefecture (Bortala) are in the second tier, supported by two or more subsystems with better comprehensive development status. Altay Prefecture, Aksu Prefecture, Kizilsu, Kashgar Prefecture, and Hotan Prefecture are in the third tier, where both water resources and agricultural planting systems have development disadvantages. Hami City and Turpan City have the poorest comprehensive development status, with grain and cotton planting system indices below 0.25.

The first and second-tier prefectures are located in Xinjiang's central geographical position, resulting in a "high in the central axis, low on both wings" spatial characteristic in the composite system's comprehensive development index. Before 2010, there was a large gap between northern and southern Xinjiang's composite development indices, which gradually narrowed afterward.

3.2 Coupling Coordination Degree Analysis

3.2.1 Spatiotemporal Characteristics of Composite System Coupling Coordination Degree From 2005 to 2019, Xinjiang's overall composite system coupling coordination degree increased from 0.410 to 0.530, a growth rate of 29.27%, showing a fluctuating upward trend. Before 2015, the composite system was in the coordinated transition zone of "barely coordinated development," and first entered the coordinated development zone of "primary coordinated development" in 2016. The coupling coordination level shows a spatial evolution characteristic of "high in the north, low in the south" (Figure [Figure 4: see original paper]).

On one hand, the improvement in coupling coordination level is related to the 逐年 increase in each subsystem's comprehensive development index. Southern Xinjiang's water resource system is developing faster than northern Xinjiang and remains at a relatively high level, causing the coupling coordination degree between northern and southern Xinjiang to continuously increase and the gap to gradually narrow. On the other hand, since the water resource system's comprehensive development level is superior to the agricultural planting system and northern Xinjiang has greater advantages, and the agricultural planting system's comprehensive development coordination shows large spatiotemporal differences among prefectures, it has gradually become a shortcoming hindering the composite system's coupling coordination development. This causes the water resource system to dominate the coupling coordination and results in a

“north-high, south-low” pattern.

From a spatiotemporal distribution perspective, in 2005, all prefectures had coupling coordination degrees below 0.5, in the barely coordinated development stage, with Kashgar and Hotan having the lowest degrees. In 2010, Karamay’s coupling coordination degree first reached 0.5, entering primary coordinated development, followed by Bayingolin, Urumqi, Ili, Tacheng, Bortala, Changji, and Aksu. Karamay and Ili were closest to the intermediate coordinated development stage. Turpan and Hami have consistently remained at low levels, below 0.45, with a significant gap compared to other regions.

3.2.2 Global Spatial Correlation Under the 0.01 significance level, Xinjiang’s composite system coupling coordination degree global Moran’s I fluctuated and decreased from 0.387 in 2005 to 0.275 in 2019 (Table), with all P-values less than 0.01. This indicates strong spatial positive correlation and clustering characteristics among Xinjiang’s prefectures, but the spatial dependence shows a weakening trend from strong to weak. Regions with high coupling coordination degrees tend to be adjacent, as do regions with low degrees. This shows that while Xinjiang’s overall composite system coupling coordination level presents a 逐年 improvement trend, the interaction effects among prefectures are gradually weakening, meaning regions tend toward autonomous development rather than being influenced by surrounding prefectures.

3.2.3 Local Spatial Correlation Patterns The composite system coupling coordination degree shows clustering phenomena in space, but clustering characteristics vary across years. In Moran scatter plots from 2005 to 2019, the fitted trend line slopes are all positive, with points in the first three quadrants accounting for 85.71% of the total, indicating that the spatial clustering of prefecture-level composite system coupling coordination degrees is relatively differentiated (Figure [Figure 5: see original paper]).

From 2005 to 2010, “high-high” clustering increased, and homogeneous development among neighboring prefectures gradually spread. The main feature evolved into regions with higher coupling coordination degrees tending to connect with similarly high neighboring regions (Figure [Figure 5: see original paper]a, b). Hami City and its neighbors easily formed spatial association tendencies where both had low coupling coordination degrees. “High-low” clustering decreased, with points in the second quadrant gradually moving to the first quadrant. By 2015, the clustering state was similar to 2010 (Figure [Figure 5: see original paper]c). By 2019, only “high-high” clustering existed in some northern Xinjiang regions, while southern Xinjiang prefectures with higher coupling coordination degrees showed insufficient radiating effects on neighboring prefectures (Figure [Figure 5: see original paper]d).

Local spatial autocorrelation analysis shows that under the 0.05 significance level, the spatial clustering pattern of Xinjiang’s composite system coupling

coordination degree is continuously evolving. In 2005, “high-high” regions included Tacheng, Karamay, Bortala, and Ili, while “low-low” regions included Kizilsu and Kashgar; other prefectures showed insignificant clustering (Figure [Figure 6: see original paper]a). By 2010, only “high-high” regions remained, while Kizilsu and Kashgar became insignificant (Figure [Figure 6: see original paper]b). By 2015, “high-high” regions remained unchanged, Hami transformed into a “low-low” region, and other prefectures maintained the same clustering types as in 2010 (Figure [Figure 6: see original paper]c). By 2019, Urumqi transformed into a “high-high” region, and other prefecture clustering types remained the same as in 2015 (Figure [Figure 6: see original paper]d).

From spatiotemporal evolution trends, Tacheng, Karamay, Bortala, and Ili easily form high-value clustering blocks with neighboring prefectures, showing a tendency toward homogeneous high development in inter-regional composite system coupling coordination degrees. Kizilsu and Kashgar are prone to forming spatial association tendencies with low coupling coordination degrees. The radiating capacity of regions with relatively good coupling coordination is very weak, especially in southern Xinjiang.

4. Discussion

Karamay’s composite system coupling coordination degree shows a relatively high level, with a low proportion of agricultural water use but high water resource development and utilization rates. Considering sustainable water resource development, it is recommended that this region reasonably regulate water consumption after improving irrigation facilities to ensure coordinated composite system development [?]. Urumqi has low levels of agricultural machinery intensity and effective irrigation area proportion, resulting in low per capita output and per-unit area yield, hindering improvements in composite system coupling coordination. Therefore, strengthening farmland water conservancy infrastructure construction is recommended to ensure benign composite system development [?]. Tacheng, Changji, Aksu, and other regions have medium-level composite system coupling coordination degrees in Xinjiang, with agricultural water use proportion exceeding 90% [?]. Increasing investment in agricultural modernization production factors, improving agricultural water-saving irrigation methods, and enhancing agricultural water use efficiency are crucial guarantees for coordinated composite system development in these regions [?]. Hami, Turpan, and other regions have low composite system coupling coordination degrees, facing significant coordinated development challenges. Therefore, strengthening local government policy guidance, gradually optimizing and upgrading agricultural industrial structure, promoting agricultural intensification, reducing production costs, decreasing water use proportion, and improving water use effectiveness are key to promoting regional composite system coupling coordination [?].

Composite system coupling coordination development is related to numerous factors. When the mutual negative influence between water resources and agri-

cultural planting is minimized, the coupling coordination stage reaches its optimal state [?]. Regions with higher coupling coordination degrees should exert their radiating effects, especially in southern Xinjiang, where prefectures can help neighboring regions enhance composite system coordination adaptability through experience sharing and knowledge/technology dissemination.

Due to data availability limitations, although the selected indicators in this study are representative, they lack comprehensiveness. Future research could improve upon this evaluation indicator system.

5. Conclusions

Taking grain and cotton planting systems as examples, this study employs the entropy weight method, coupling coordination degree model, and exploratory spatial data analysis to investigate the temporal evolution patterns and spatial clustering characteristics of Xinjiang's composite system coupling coordination development from 2005 to 2019. The main conclusions are:

- (1) Xinjiang's composite system comprehensive development index shows a spatial pattern of "high in the central axis and low on both wings." The water resource system maintains a relatively high overall level, while the agricultural planting system demonstrates a faster growth trend. The mean composite system comprehensive development index never exceeded 0.4, indicating a relatively low overall level with certain differences in comprehensive development status of the two subsystems across prefectures. The water resource system's comprehensive development index shows large spatiotemporal differences, with long-term differences exceeding 0.3 between the highest and lowest prefectures, presenting a "north-high, south-low" spatial distribution pattern.
- (2) Xinjiang's composite system coupling coordination level showed gradual growth from 2005 to 2019, first entering the coordinated development zone and reaching the primary coordinated development stage in 2016, presenting a "north-high, south-low, but gradually narrowing gap" development trend. The composite system coupling coordination degree fluctuated upward from 0.410 to 0.530, with southern Xinjiang showing faster growth than northern Xinjiang. The agricultural planting system's comprehensive development coordination has become a bottleneck hindering composite system coupling coordination development due to large spatiotemporal differences among prefectures. Moreover, regions with relatively good coupling coordination have weak radiating capacity to neighboring regions. However, as water resource conditions continue to improve, the gap in coupling coordination levels between northern and southern Xinjiang will gradually narrow. Additionally, Turpan and Hami in northern Xinjiang show lagging coordinated adaptation in composite systems.
- (3) Xinjiang's composite system coupling coordination degree shows significant spatial positive correlation clustering characteristics that are weaken-

ing from strong to weak. The spatial clustering type is mainly “high-high and low-low” clustering, with the composite system coupling coordination degree showing obvious spillover effects and being easily influenced by neighboring regions. Locally, neighboring regions show homogeneous development status, while high-coordination regions in southern Xinjiang exhibit insufficient positive radiating effects. This urgently requires policies that regulate and expand resource endowment sharing and digital information technology promotion in agricultural industries among neighboring regions to achieve composite system coupling coordination across Xinjiang.

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