Postprint: Coupling Coordination Degree of Explicit-Implicit Morphology of Cultivated Land Use in Northwest China' s Farming System Region

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Abstract

Thorough investigation into farmland use patterns is of great significance for achieving efficient farmland utilization and ensuring food security. This study constructs a comprehensive evaluation index system for farmland use patterns, employs spatiotemporal statistical methods to examine the spatiotemporal evolution characteristics of the coupling coordination degree between "explicit-implicit" patterns of farmland use in the northwestern farming system region of China from 2010 to 2021, and utilizes an obstacle degree decomposition model to analyze obstacle indicators of farmland use. The results indicate: (1) The explicit and implicit patterns of farmland use in the northwestern farming system region of China exhibit asynchronous development, with significant regional differentiation in lagging development; the coupling coordination degree between "explicit-implicit" patterns of farmland use remains at a low level, and all sub-regions display pronounced polarized distribution characteristics. (2) Intra-regional differences in the coupling coordination degree of "explicit-implicit" farmland use patterns exhibit a fluctuating declining trend, while the contribution rate of inter-regional differences gradually increases, becoming the primary source of overall differences, with all sub-regions demonstrating spatial convergence characteristics. (3) Farmland use is primarily constrained by factors including farmland quantity structure, landscape characteristics, intensification level, and production function. Targeting these factors as key priorities, efforts should be made to enhance the rational utilization of water resources, promote the protection and development of suitable farmland, mitigate the constraints imposed by obstacle indicators, and facilitate the coupled development of "explicit-implicit" farmland use patterns, thereby providing scientific references for the sustainable development of farmland use in the northwestern farming system region of China.

Full Text

Preamble

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Study on the "Explicit-Implicit" Patterns Coupling Coordination Degree of Cropland Utilization in the Farming System of Northwest China

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Abstract

Studying cropland utilization patterns is crucial for achieving efficient cropland use and ensuring food security. This study explores the spatiotemporal evolution characteristics of the "explicit-implicit" patterns coupling coordination degree of cropland utilization in the farming regions of northwest China from 2010 to 2021. A comprehensive evaluation index system of cropland utilization patterns was constructed, and spatiotemporal statistical methods were employed. The obstacle factors of cropland utilization were analyzed using the barrier degree decomposition model. The results showed that: (1) The explicit and implicit patterns of cropland utilization in northwest China' s farming systems developed asynchronously, with significant regional differentiation and backward development. The coupling coordination degree between explicit and implicit patterns of cropland utilization remained low, exhibiting a pronounced polarization in each sub-region. (2) The intra-regional differences in the coupling coordination degree of "explicit-implicit" patterns of cropland utilization displayed a fluctuating downward trend, while the contribution rate of inter-regional differences gradually increased, becoming the main source of overall variation. Each sub-region demonstrated spatial convergence characteristics. (3) Cropland utilization is primarily constrained by factors such as cropland quantity structure, landscape characteristics, intensive level, and production function. To address these limitations, the study suggests improving the rational use of water resources, promoting the protection and development of suitable cultivated land, and alleviating the impact of obstacle factors. These measures aim to develop a suitable farming system and enhance the coupling development of "explicit-implicit" patterns of cropland utilization, providing a scientific reference for the sustainable development of cropland utilization in the farming systems of northwest China.

Keywords: farming system; cropland utilization; explicit pattern; implicit pattern; coupling coordination degree

Introduction

Cropland serves as the spatial carrier of agricultural production, and its utilization patterns reflect the complex interactions between humans and the "natural-social" environment [1]. Trend-based changes in cropland use over long time sequences provide the foundation for understanding cropland use transition, which plays a vital role in ensuring food security, promoting agricultural economic growth, and maintaining social stability [2]. For a long time, China has faced quantitative challenges in cropland resources—characterized by abundant total area but limited per capita availability and insufficient reserve resources [3]. Current research hotspots in this field focus on theoretical frameworks of cropland use transition [4], morphological characteristics [5], driving mechanisms [6], implementation pathways [7], and external effects on rural issues [8].

In addition to quantitative problems, China also faces elemental issues such as aging and weakening of agricultural labor forces, cropland fragmentation, and quality deterioration, as well as structural problems like cropland conversion to non-agricultural and non-grain uses [9]. These issues severely constrain the sustainable development and utilization of cropland resources and hinder the steady advancement of rural revitalization and agricultural power strategies. The 2022 Central Rural Work Conference proposed "protecting cropland as the lifeblood, ensuring both quantity guarantee and quality improvement," and the 2023 No. 1 Central Document further clarified the need to "strictly implement the cropland protection system and improve the 'three-in-one' protection system for cropland quantity, quality, and ecology," setting specific targets for cropland utilization development in the new stage.

China' s agricultural production is influenced by a combination of geographical elements (geology, topography, climate, hydrology), production factors (labor, capital, cropland), and socio-economic elements (ethnicity, culture, infrastructure, industrial structure) [10]. Cropland utilization patterns exhibit long-term conflicts between explicit and implicit morphological structures. Current research often focuses on single morphological aspects (either explicit or implicit) of cropland utilization, typically at provincial scales, neglecting regional differences and imbalances in agricultural development across different areas. This makes it difficult to systematically evaluate the overall characteristics of cropland use transition and reveal the underlying obstacles causing conflicts.

In summary, cropland use morphological change is a dynamic process of linkage and interaction between explicit and implicit patterns. While explicit pattern changes represent the direct spatial expression of cropland resources, implicit pattern changes are also reflected in geographical space [11]. Whether these two patterns can develop synergistically is the key to high-quality cropland use transition. Based on this understanding, this study examines 87 counties (districts) in the farming system region of northwest China as research units to analyze the spatiotemporal evolution characteristics and obstacle factors of the "explicit-implicit" patterns coupling coordination degree of cropland utilization. The potential marginal contributions are: First, using farming system zoning to delineate the study area represents a practical grasp and solution to differentiated cropland utilization problems under China' s unique agricultural conditions. Second, constructing a comprehensive evaluation index system for "explicit-implicit" patterns of cropland utilization using diversified basic indicators helps systematically and multi-dimensionally identify core issues in cropland utilization.

1.1 Study Area Overview

The northwest farming system region, also known as the northwest arid mid-temperate oasis irrigation farming system combined with desert grazing area [12], primarily covers Xinjiang, western Inner Mongolia, northwestern Gansu, and northern Ningxia. This region encompasses 87 counties and includes four major irrigation areas stretching across the northwest arid region, as well as complex terrains such as desert grasslands, deserts, gobi, and sand dunes. Cropland area accounts for only 4.3% of total land area, facing obvious constraints in both quantity and quality. The farming system comprises three sub-regions (Figure 1): Sub-region I (Hetao-Hexi irrigation single-crop fallow farming area and Alxa Highland desert pastoral area), Sub-region II (Northern Xinjiang irrigation and dryland single-crop fallow farming area and desertified pastoral area), and Sub-region III (Southern Xinjiang irrigation single-and-double-crop farming area and desertified pastoral area).

1.2 Concepts and Representation

Consistent with the distinction in land use morphology [13], cropland utilization patterns include both explicit and implicit types. The explicit pattern reflects the composition structure of regional cropland use types within a specific period, including quantitative and spatial structures [14]. The implicit pattern, which relies on the explicit pattern, requires analysis, testing, and investigation to obtain, encompassing multiple attributes such as quality, property rights, management methods, inputs, outputs, and functions [15]. Based on the conceptual connotations of "explicit-implicit" cropland use patterns and considering data availability, this study constructed evaluation index systems for both explicit and implicit patterns (Table 1).

1.3 Data Sources

Socio-economic data were obtained from the *China County Statistical Yearbook*, *China Rural Statistical Yearbook*, statistical yearbooks of various counties (districts), and *National Economic and Social Development Statistical Bulletins*. Cropland coverage data were sourced from the annual land cover dataset for China (1985-2021) produced by Professors Yang Jie and Huang Xin from Wuhan University. Cropland landscape indices were calculated using ArcGIS and Fragstats software. Missing data were filled using linear interpolation and short-term estimation methods. The study period was defined as 2010-2021. Considering administrative changes during this period, the 2021 administrative divisions were used as the baseline, and areas with severe data gaps were excluded, resulting in 87 valid analysis units.

1.4 Methodology

1.4.1 Coupling Coordination Degree Model

The entropy weight method was used to calculate the explicit and implicit pattern indices of cropland utilization [16]. The coupling coordination degree model was then introduced to characterize the relationship between "explicit-implicit" patterns, with the following formulas [17]:

$$C = 2\sqrt{\frac{S_1 \times S_2}{(S_1 + S_2)^2}}$$

$$T = \alpha S_1 + (1 - \alpha) S_2$$

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

where C is the coupling degree; T is the comprehensive coordination index of the two subsystems (explicit and implicit patterns); S_1 and S_2 are the explicit and implicit pattern indices of cropland utilization; D is the coupling coordination degree; and α is an undetermined coefficient reflecting the contribution of subsystems to cropland utilization level, set as $\alpha = 0.5$.

1.4.2 Kernel Density Estimation

Kernel density estimation was employed to identify the dynamic evolution patterns of the "explicit-implicit" patterns coupling coordination degree of cropland utilization. Using the Gaussian kernel function, the specific process is as follows [18]:

$$f(x) = \frac{1}{nh} \sum_{i=1}^{n} K\left(\frac{x - x_i}{h}\right)$$

where $K(x)$ is the kernel function; n is the number of observations; h is the bandwidth; x_i is the observation value (coupling coordination degree); and $\bar{x}$ is the mean of observations.

1.4.3 Dagum Gini Coefficient

The Dagum Gini coefficient decomposition was used to examine spatial inequality issues. This method not only addresses the sources of regional differences but also overcomes the cross-overlap defects between sample groups [19]. The calculation formulas are:

$$G = \sum_{j=1}^{k} \sum_{h=1}^{k} \sum_{i=1}^{n_j} \sum_{r=1}^{n_h} \frac{|y_{ji} - y_{hr}|}{2n^2 \bar{y}}$$

$$G_w = \sum_{j=1}^{k} G_{jj}$$

$$G_{nb} = \sum_{j=2}^{k} \sum_{h=1}^{j-1} G_{jh}$$

$$G_t = G_w + G_{nb} + G_t$$

where G is the overall Gini coefficient (larger values indicate greater overall disparity); k is the number of sub-regions; n is the total number of counties (districts); n_j and n_h are the numbers of counties in regions j and h; y_{ji} and y_{hr} are the coupling coordination degree values for counties i and r in regions j and h; $\bar{y}$ is the overall average coupling coordination degree; G_w represents intra-regional differences; G_{nb} represents inter-regional differences; G_t represents transvariation density differences; G_{jj} is the Gini coefficient within region j; G_{jh} is the Gini coefficient between regions j and h; B_{jh} is the relative impact of coupling coordination degree between regions j and h; b_{jh} is the mathematical expectation of sample values satisfying $y_{ji} - \bar{y}_h > 0$ in regions j and h; c_{jh} is the mathematical expectation of sample values satisfying $y_{hr} - \bar{y}_j > 0$; and F_j and F_h are the cumulative density distribution functions for regions j and h.

1.4.4 Spatial Convergence Model

The absolute β convergence model was used to test the spatiotemporal evolution characteristics of the "explicit-implicit" patterns coupling coordination degree of cropland utilization:

$$\ln\left(\frac{D_{i,t+1}}{D_{i,t}}\right) = \alpha + \beta \ln(D_{i,t}) + \theta \sum_{j=1}^{n} w_{ij} \ln(D_{j,t}) + \rho \sum_{j=1}^{n} w_{ij} \ln\left(\frac{D_{j,t+1}}{D_{j,t}}\right) + u_i + v_t + \varepsilon_{it}$$

where $D_{i,t+1}$ and $D_{i,t}$ are the coupling coordination degrees of county (district) i in periods $t+1$ and t; $\ln(D_{i,t})$ is the logarithm of the coupling coordination degree; α is the constant term; θ and ρ are spatial coefficients to be estimated; u_i is the regional effect; v_t is the time effect; ε_{it} is the random disturbance term; w_{ij} is the spatial weight matrix between counties (districts) i and j; and β is the convergence coefficient. If $\beta < 0$ and significant, the coupling coordination degree exhibits convergence characteristics. Equation (4) represents the Spatial Durbin Model (SDM). When $\theta = 0$, it becomes the Spatial Lag Model (SAR); when $\rho = 0$, it becomes the Spatial Error Model (SEM).

1.4.5 Obstacle Degree Decomposition Model

The obstacle degree decomposition model was used to identify the degree to which each basic indicator in the evaluation index system hinders the coupling coordination degree [20]:

$$T_{ij} = 1 - x'_{ij}$$

$$Q_{ij} = \frac{T_{ij}W_j}{\sum_{j=1}^{m} T_{ij}W_j} \times 100\%$$

where T_{ij} is the deviation degree of indicator j in county (district) i; x'_{ij} is the standardized value of indicator j in county (district) i; W_j is the weight of indicator j; and Q_{ij} is the obstacle degree of indicator j in county (district) i (higher values indicate greater inhibition of the "explicit-implicit" patterns coupling coordination degree).

2.1 Spatiotemporal Evolution Characteristics of "Explicit-Implicit" Patterns Coupling Coordination Degree

2.1.1 Spatial Distribution Pattern of "Explicit-Implicit" Patterns

According to the calculation results, the overall level of "explicit-implicit" patterns coupling coordination degree in northwest China' s farming system region was below 0.55, with evaluation criteria ranging only between 0-0.55 (Table 2). To further explore the synchronous development relationship between explicit and implicit pattern levels, the ranking difference between the two indices was used to determine relative lag types [21]. If the ranking gap between a county' s explicit and implicit pattern indices was within 5 positions, it indicated synchronous development (synchronous type). If the explicit pattern index ranked more than 5 positions ahead of the implicit pattern index, it indicated better explicit development (implicit-lag type), and vice versa (explicit-lag type).

Synchronous development relationships were rare in northwest China' s farming system region, with explicit-lag or implicit-lag types being predominant (Figure 2). Sub-region I mainly exhibited implicit-lag and explicit-lag types, with explicit-lag types concentrated in the central part and implicit-lag types in the eastern part. This distribution stems from topographic differences: the eastern area consists of plain oases while the central area features highland desert terrain, creating different agricultural development conditions and spatial imbalances in cropland utilization. Sub-region II showed distinct clustering characteristics, with implicit-lag types concentrated in the western areas around the Manas River basin and oases in Yili, Tacheng, and Altay with higher precipitation. This reflects the positive role of water resources in irrigated dryland areas in improving cropland utilization levels, while eastern areas dominated by deserts and grasslands have limited cropland quantity, constraining explicit pattern development. Sub-region III was dominated by explicit-lag types, also due to being surrounded by mountains and the Taklamakan Desert, causing explicit pattern lag.

2.1.2 Dynamic Evolution Characteristics

Kernel density estimation using Matlab revealed the dynamic evolution characteristics of the coupling coordination degree (Figure 3). The overall curve showed no significant shift in central position, concentrating in the 0.3-0.4 range with moderate and mild 失调 types. The main peak height gradually increased while width narrowed, indicating reduced imbalance and emerging agglomeration. The pronounced right tail suggested some counties had significantly higher coupling coordination degrees than the average, with the absolute gap gradually widening. The multi-peak distribution indicated obvious multi-polarization.

Sub-regions showed varying characteristics (Figure 3). Sub-region I' s curve showed no major shift, maintaining low levels. The main peak height first decreased then increased, with corresponding width first broadening then narrowing, indicating alleviated dispersion. Sub-region II's "double peaks" continuously narrowed while rising, showing shrinking differences among counties with similar coordination levels. Sub-region III' s curve height first decreased then increased, indicating narrowing intra-regional differences. Sub-region IV' s curve remained relatively flat with stable intra-regional differences. Regarding distribution extension, sub-regions I, II, and III all showed right-tail features, indicating some counties significantly exceeded average levels. Polarization analysis revealed sub-region I had one main peak and one side peak (slight two-level differentiation). Sub-region II exhibited a "multi-peak pattern" with high "double peaks" and multiple lower side peaks (obvious multi-level differentiation). Sub-region III' s curve evolved from "main-side peak" to "main-multiple side peaks," with increasing side peaks intensifying multi-polarization.

2.1.3 Regional Differences and Sources

Overall and Intra-regional Differences: The overall Gini coefficient and intra-regional Gini coefficients showed that from 2010-2021, the overall Gini coefficient fluctuated between 0.08-0.10, displaying a downward trend (Figure 4). Mean intra-regional Gini coefficients varied by sub-region: Sub-region I (0.09), Sub-region II (0.08), Sub-region III (0.07), and Sub-region IV (0.06). Sub-region I had the largest intra-regional differences due to contrasting conditions—featuring both well-endowed areas like the Ningxia Hetao Plain and Gansu Hexi Corridor oases, and low-potential areas like the Alxa Highlands and western Ordos Plateau deserts where limited cropland quantity creates explicit pattern differences. Sub-region I' s intra-regional differences remained high, Sub-region II showed multi-stage decline with narrowing differences, and Sub-region III remained relatively stable.

Inter-regional Differences: Inter-regional Gini coefficients between sub-regions showed that differences between Sub-region I and others were relatively high, declining by 4.76% (Figure 4). Differences between Sub-regions II, III, and IV were smaller (mean 5.84%) because these regions share similar characteristics of irrigation intensification and cotton-based farming systems.

Difference Sources: The contribution to overall differences remained stable: intra-regional differences contributed about 50.72%, transvariation density differences fluctuated around 33.13-34.69%, and inter-regional differences increased from 16.15% to 36.12%, becoming the primary source of overall differences and indicating deepening inter-regional disparities.

2.1.4 Spatial Convergence Characteristics

Using a geographic distance matrix and Hausman test, the spatial convergence analysis model was determined for the overall region and sub-regions (Table 3). First, convergence coefficients for the overall region, sub-regions I, II, and III were significantly negative at the 1% level, indicating spatial convergence and possible convergence toward a steady state. Second, based on absolute convergence coefficient values, sub-regions I, II, and III showed faster convergence speeds. This resulted from successive cropland protection, development, and utilization policies that maintained the "three-in-one" protection of quantity, quality, and ecology, effectively curbing cropland conversion to non-agricultural and non-grain uses and improving explicit-implicit pattern coordination. Sub-region IV had relatively higher coupling coordination degrees, thus slower convergence speed.

2.2 Decomposition of Obstacle Factors

The obstacle degree decomposition model was applied to rank obstacle degrees of indicators in the 87 counties across three sub-regions, with the top three indicators identified as primary obstacles (Table 4).

2.2.1 Obstacle Factors for Explicit Patterns

First, the obstacle degree of cropland landscape separation index exceeded 37.85% across all sub-regions, indicating cropland fragmentation as the primary obstacle. Northwest China' s farming system region suffers from severe cropland fragmentation [22], hindering intensive and large-scale utilization. With the popularization of agricultural mechanization and rising labor costs, fragmented cropland increases agricultural costs and causes inefficient utilization. Second, the grain-cash crop ratio obstacle degree exceeded 17.52%, showing that cropland "non-grain" use significantly impedes utilization. As a national base for cotton and fruits, the region' s large economic crop planting area threatens food security, alters soil fertility, reduces cropland quality, and affects production capacity and sustainability. Third, the land reclamation rate obstacle degree exceeded 16.30%. The region accounts for 24.6% of China' s land area but only 8.9% of cropland, with an reclamation rate of just 4.3%, severely limiting explicit pattern levels due to arid desert climate and fragile ecology.

2.2.2 Obstacle Factors for Implicit Patterns

First, the obstacle degree of primary industry output value per unit cropland area exceeded 55.41%, representing the primary obstacle. Constrained by geographical natural elements, the region' s primary industry development is poor, with virtually no forestry or fisheries, highly desertified natural grasslands limiting animal husbandry, and low-level crop production forming the core barrier to improving implicit pattern levels. Second, the obstacle degree of grain yield per unit cropland area exceeded 16.60%, serving as the second major obstacle for the overall region and sub-regions I, II, and III. Sub-region IV has higher "non-grain" degrees than other sub-regions, affecting food security capacity. Third, the multiple cropping index obstacle degree exceeded 16.20%, indicating that intensification level is a major obstacle. Influenced by topography and location, poor transportation conditions and limited agricultural resource inputs and technology applications hinder intensive cropland utilization.

Discussion

This study constructed a "explicit-implicit" patterns evaluation index system for cropland utilization, measured pattern levels in northwest China' s farming system region using the entropy weight method, introduced the coupling coordination degree model to examine coordinated development, and revealed spatiotemporal evolution characteristics through Kernel density estimation, Dagum Gini coefficient, and spatial convergence tests. The obstacle degree decomposition model identified limiting factors, providing references for coordinated cropland utilization. Compared with previous studies focusing on administrative scales [23], this research incorporates farming system zoning to deepen the research scale. Unlike studies examining single morphological patterns [24], it further subdivides cropland utilization patterns into explicit and implicit types, enriching the connotation and extension of the cropland utilization system.

Based on measurement and spatiotemporal analysis results, we propose strategies for advancing cropland utilization development in northwest China' s farming system region:

(1) Rational water use is key for this dryland farming system region.

First, construct water storage projects to improve water resource allocation reserves, alleviate the "water-determines-land"phenomenon, optimize spatiotemporal water use patterns, and effectively improve water resource security capacity to mitigate resource-based and regional water shortages in northwest arid areas while promoting water-saving utilization and preventing soil secondary salinization from extensive irrigation. Second, sub-region IV has low water resource utilization rates and significant development potential. On an ecological protection basis, expand the development and utilization of unconventional water resources to improve ecological conservation capacity.

(2) As an ecologically fragile region, northwest China' s farming system should conduct land suitability evaluation and implement protective development of suitable cropland. The region has vast land resources but low reclamation rates and considerable development potential. By evaluating cropland reserve resources and considering environmental carrying capacity, suitable cropland can be developed while unstable cropland types undergo ecological restoration and comprehensive management to improve cropland resource reserve management.

(3) Given obvious spatial differences in natural resource endowments, the region should leverage location advantages to develop suitable farming systems. Sub-region I can develop characteristic agriculture based on water resource distribution, with the Hexi Corridor utilizing its proximity to the Yellow River basin to develop irrigation agriculture and become a characteristic agricultural production base. Sub-region II can leverage its light and heat advantages to develop characteristic "sunshine crop" farming systems and increase farmer income.

Based on obstacle degree decomposition results, we discuss strategies to alleviate obstacle constraints:

(1) Mitigate the negative impact of cropland fragmentation by advancing fragmentation governance tailored to regional natural characteristics, promoting concentrated and contiguous cropland use, and optimizing cropland utilization patterns.

(2) Prevent further "non-grain" intensification, protect existing grain planting areas, and adapt agricultural planting structures to local conditions to create planting systems balancing ecological and economic benefits.

(3) Promote agricultural technology innovation, develop characteristic agriculture, introduce specialized technologies, and advance the popularization of agricultural mechanization to achieve large-scale, intensive cropland utilization, improve production efficiency, and increase agricultural value.

Conclusion

This study reached the following conclusions:

(1) From 2010-2021, the explicit and implicit patterns of cropland utilization in northwest China's farming system region developed asynchronously, with significant regional differentiation in lagging development. The "explicit-implicit" patterns coupling coordination degree remained low with stable trends, and each sub-region exhibited obvious polarization distribution characteristics.

(2) Intra-regional differences in the coupling coordination degree showed fluctuating decline, while inter-regional difference contributions gradually increased to become the primary source of overall variation. Spatial convergence analysis revealed convergence characteristics in both the overall region and sub-regions, though convergence speeds varied.

(3) Obstacle degree decomposition results showed that for explicit patterns, significant deficiencies existed in cropland quantity and landscape morphology, with cropland landscape separation index, grain-cash crop ratio, and land reclamation rate as major obstacles. For implicit patterns, the multiple cropping index, grain yield per unit area, and primary industry output value per unit area were major obstacles, indicating that insufficient production function severely limited cropland utilization in northwest China's farming system region.

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