Evolution of Territorial Spatial Functions and Synergistic/Trade-off Relationships: A Case Study of the Hohhot-Baotou-Ordos Region, Inner Mongolia (Postprint)

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Abstract

Territorial space faces issues such as extensive resource utilization, ecological environment destruction, and unbalanced regional development; clarifying territorial space functions is conducive to coordinated regional development. Taking 1990, 2000, 2010, and 2018 as observation periods, and based on analyzing the evolution characteristics of territorial space functions in the Hohhot-Baotou-Ordos region, this study employs the coupling coordination degree and bivariate spatial autocorrelation model to evaluate the synergy/trade-off relationships in the evolution of territorial space functions. The results show that over the past 28 years, the production/living functions in the study area have increased locally, with spatial distribution presenting a concentric/semi-concentric pattern centered on municipal districts as high-value centers and decreasing outward in gradient; ecological functions have declined, with spatial distribution exhibiting a natural landscape scale-dependent effect; the coupling coordination degree of territorial space functions has increased overall, with the number of banners and counties showing synergistic relationships increasing, but the overall level remains low; spatial differentiation manifests as an agglomerated distribution of synergy/trade-off relationships between production-living functions; the synergy/trade-off relationships between production/living-ecological functions tend to be discrete; the spatial coupling effect level of synergy/trade-off relationships among various functions is low, and territorial space functions urgently need adjustment and optimization.

Full Text

Study on the Evolution and Synergy/Trade-off Relationships of Territorial Spatial Functions: A Case Study of the Hohhot-Baotou-Ordos Region, Inner Mongolia

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Abstract

Territorial space faces challenges including extensive resource utilization, ecological environmental degradation, and unbalanced regional development. Clarifying territorial spatial functions is essential for promoting coordinated regional development. This study examines the Hohhot-Baotou-Ordos region during the observation periods of 1990, 2000, 2010, and 2018. Based on an analysis of the evolutionary characteristics of territorial spatial functions, we employ the coupling coordination degree model and bivariate spatial autocorrelation model to evaluate the synergy/trade-off relationships in the evolution of these functions. The results indicate that: (1) Over the past 30 years, production and living functions have increased locally in the study area, with spatial distribution exhibiting a circular/semi-circular pattern centered on municipal districts and decreasing outward in gradient; (2) Ecological function has declined overall, with spatial distribution demonstrating a scale-dependent effect of natural landscapes; (3) The coupling coordination degree of territorial spatial functions has increased overall, with the number of banner counties showing synergistic relationships rising, yet the overall level remains low; (4) Spatial differentiation manifests as clustered distribution of synergy/trade-off relationships between production and living functions, while synergy/trade-off relationships between production and ecological functions tend toward dispersion; (5) The spatial coupling effect of synergy/trade-off relationships among various functions is at a low level overall, indicating an urgent need for adjustment and optimization of territorial spatial functions.

Keywords: territorial spatial functions; production-living-ecological space; synergy/trade-off relationship; Hohhot-Baotou-Ordos region

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Introduction

Function represents the capacity exhibited by a system with a specific structure during material exchange with its external environment. As an important manifestation of territorial spatial utilization patterns, functional evolution reflects the degree to which the development needs of multiple stakeholders within territorial space are satisfied. Territorial space is a spatial system composed of multiple functions. The conceptual extension of territorial space divides it into production, living, and ecological functions. Production function treats land as either a production object or a production carrier to output various products and services. It serves as the material foundation for living and ecological functions, supporting quality of life improvements and ecological environment maintenance, though its expansion can encroach upon ecological functions. Living function, as an important carrier of human settlements, primarily provides residence, work, commuting, and recreation. Its enhancement requires ecological function maintenance, while living function improvement strengthens production function expansion. However, living function expansion also encroaches upon production and ecological functions. Ecological function is the foundation of territorial spatial functions, providing external conditions necessary for the normal operation of production and living functions. Only through mutual cooperation and coordinated development among territorial spatial functions can comprehensive land benefits be maximized. This dynamic game reflects the reallocation of land resources in terms of quantity and space among functions. Synergy refers to mutual cooperation and joint gains among territorial spatial functions, reflecting coordinated order through functional integration. Trade-off refers to the mutually constraining relationship where functions compete and conflict, manifested as spatial conflicts and competition among functional spaces. Different intensities of functional changes cause synergy/trade-off relationships among territorial spatial functions to evolve alternately.

Common methods for territorial spatial function identification include direct classification and quantitative evaluation. The former classifies land directly according to dominant functions, while the latter constructs indicator systems based on land multifunctionality. Evaluation results aim to analyze dominant functions at administrative unit scales or employ specific methods to measure land service values. With mature geographic information technology applications, territorial spatial function identification using multi-source data has become mainstream, though data source limitations prevent evaluation of long-term functional evolution. Previous research has focused on economically developed regions undergoing rapid industrialization and urbanization, while studies on ecologically vulnerable areas remain relatively insufficient.

The Hohhot-Baotou-Ordos region (Hohhot City, Baotou City, and Ordos City) in Inner Mongolia represents a typical ecologically vulnerable and resource-rich area. Resource-driven growth constitutes one of its primary economic development models, creating particularly prominent contradictions between economic construction and ecological protection. Additionally, this region benefits from multiple national policy supports including the Yellow River Basin ecological protection and high-quality development initiative and the China-Mongolia-Russia economic corridor. Using the Hohhot-Baotou-Ordos region as a case study holds strong representativeness and typicality for exploring sustainable territorial spatial development in ecologically vulnerable areas.

This study constructs a territorial spatial function evaluation system for the Hohhot-Baotou-Ordos region, analyzes the evolutionary characteristics of production, living, and ecological functions, and evaluates the synergy/trade-off relationships in functional evolution using coupling coordination degree and bivariate spatial autocorrelation models. The aim is to provide a foundation for territorial spatial development and protection in the study area and offer reference for similar regions.

1.1 Study Area Overview

The Hohhot-Baotou-Ordos region is located in central-western Inner Mongolia, between 37°37 -42°44 N and 106°31 -112°17 E, comprising three prefecture-level administrative units: Hohhot City, Baotou City, and Ordos City, covering an area of approximately 13.18$×10^{4}$ km^2. The terrain consists primarily of plateaus and medium-low mountains at elevations between 816–2338 m. The climate belongs to the semi-arid continental monsoon type, characterized by low precipitation with high variability and limited total water resources. The main stream of the Yellow River flows through the region from west to southeast, forming a right-half "几" shaped structure. According to 2018 land use types, the proportions of first-level land categories from highest to lowest are: grassland (59.42%), unused land (18.91%), cultivated land (11.55%), forest land (4.26%), and construction land (3.72%). Ecological land holds an absolute advantage. Territorial spatial development focuses primarily on agricultural, pastoral, and industrial-mining production. By the end of 2018, the region' s permanent resident population was 809.35$×10^{4}$ people, with an urbanization rate of 75.93% and a regional GDP of 8512.68$×10^{8}$ yuan. The region features diverse energy resources, with abundant coal, oil and gas, iron ore, and rare earth resources. The resource-driven economic growth model has led to frequent ecological problems including land degradation and environmental pollution.

[Figure 1: see original paper]

1.2.1 Construction of the Territorial Spatial Function Evaluation Indicator System

At the macro scale, territorial space can be defined through "production-living-ecological" functions. Production function space refers to areas dominated by providing industrial, agricultural, and service products; living function space refers to areas dominated by providing human residence and leisure; ecological function space refers to areas dominated by providing ecological products and services. The indicator system is constructed from the target layer downward. Specific evaluation indicators are shown in Table 1. Multi-source data are used, with land use vector data from the Resource and Environmental Science and Data Center of the Chinese Academy of Sciences. Production function land includes cultivated land and industrial-mining land; living function land includes urban and rural residential land; ecological function land includes forest land, grassland, water areas, and unused land. Economic data are sourced from the Inner Mongolia Statistical Yearbook (1991–2019), supplemented by prefecture-level city statistical yearbooks.

Production function increases social wealth through agricultural and industrial-mining production spaces. Agricultural and pastoral products provide raw materials for industrial production, while improved industrial production capacity feeds back to agricultural production efficiency. Together they provide economic benefits for regional development. Food security is represented by grain yield per unit area, per capita grain possession, and per capita livestock product output. Agricultural production efficiency and intensity are represented by land reclamation rate, per capita pasture area, output value per unit area of agriculture, forestry, animal husbandry, and fishery, and agricultural mechanization level. To objectively reflect regional production efficiency, a series of construction land per-unit-area indicators represent non-agricultural production functions.

Living function examines housing, medical care, and education conditions. Residential and transportation carrying capacity is represented by the proportion of urban-rural residential land, per capita housing area, and transportation land density. Employment support capacity is represented by secondary and tertiary industry employment density. Living consumption levels are represented by per capita postal and telecommunications business volume, rural per capita electricity consumption, per capita total retail sales of consumer goods, and the urban-rural resident income balance index. Social security in medical care and education is represented by the number of hospital beds per 10,000 people and the number of primary and secondary school students per 1,000 people.

Given the ecologically sensitive and fragile nature of the study area, ecological function is represented by indicators measuring regional ecological security levels. Specific indicators include the natural disaster index, cultivated land non-point source pollution pressure index, and landscape ecological risk index to characterize ecological risk levels. Ecological sensitivity is characterized by biological abundance index, water network density index, per capita ecological space area, forest and grass coverage rate, and vegetation net primary productivity. Human regulation capacity of ecological space is represented by per-unit-area ecosystem service value and ecological elasticity degree.

Partial indicator calculations are explained as follows: (1) Production function: grain yield per unit area is the ratio of grain output to cultivated land area; land reclamation rate is the ratio of cultivated land area to total regional land area; agricultural mechanization level is the ratio of total agricultural machinery power to cultivated land area. (2) Living function: transportation land density is the ratio of highway mileage to total regional area; urban-rural resident income balance index is the ratio of per capita net income of rural residents to per capita disposable income of urban residents. (3) Ecological function: cultivated land non-point source pollution pressure index is the ratio of converted pure quantity of chemical fertilizer and pesticide application to cultivated land area; biological abundance index, water network density index, natural disaster index, per-unit-area ecosystem service value, ecological elasticity degree, and landscape ecological risk index are detailed in references [27–30]; other indicators can be calculated directly according to their definitions.

1.2.2 Evaluation Methods for Territorial Spatial Function Evolution

To ensure scientific and reasonable evaluation results, the entropy weight method and analytic hierarchy process (AHP) are combined to determine indicator weights. The entropy weight method determines objective weights based on indicator variability—the greater the information provided by an indicator, the higher its weight. Compared with other objective weighting methods (coefficient of variation method, principal component analysis), the entropy weight method better distinguishes indicators. Specific calculation methods are detailed in reference [31]. AHP systematizes, models, and quantifies decision-making thinking for complex phenomena, reducing subjective scoring impacts through consistency tests, thus offering advantages in calculating indicator weights for complex systems. Specific calculation methods are detailed in reference [32].

Linear operations are performed on objective weights determined by the entropy method and subjective weights determined by AHP to obtain final indicator weights:

$$\xi_j = \frac{\omega_j \mu_j}{\sum_{j=1}^{n} \omega_j \mu_j}$$

where ξ_j is the specific weight of each indicator; ω_j is the weight determined by the entropy method; μ_j is the weight determined by AHP; j is the indicator number in each target layer, $j = 1, 2, \cdots, n$. The calculation results of each indicator weight are shown in Table 1. Finally, a linear weighting method constructs the comprehensive evaluation model for territorial spatial functions:

$$ES = \sum_{j=1}^{n} \xi_j \times y_{ij}$$

where ES is the function value of each target layer, S represents each target layer, $S = P, L, E$; a larger ES value indicates higher functional level of the corresponding target layer; y_{ij} is the range-standardized result of each indicator.

1.2.3 Analysis Methods for Synergy/Trade-off Relationships of Territorial Spatial Functions

(1) Coupling Coordination Model

Based on analyzing the spatio-temporal evolution characteristics of territorial spatial functions, a functional coupling coordination model is constructed. The coupling degree model for three systems (or internal system elements) is expressed as:

$$C = 3 \times \frac{\sqrt[3]{P_i \times L_i \times E_i}}{P_i + L_i + E_i}$$

where C is the coupling degree of territorial spatial functions; P_i, L_i, E_i represent production, living, and ecological function values, respectively. The coupling coordination degree of territorial spatial functions is calculated as:

$$D = \sqrt{C \times T}, \quad T = \alpha P_i + \beta L_i + \gamma E_i$$

where D is the coupling coordination degree of territorial spatial functions; T is the comprehensive coordination degree; α, β, γ are 待定 coefficients for the three functions. Referencing relevant studies [33] and expert opinions, $\alpha = \beta = \gamma = 0.35$.

The coupling coordination degree is divided into trade-off relationships $[0, 0.5)$ and synergy relationships $[0.5, 1]$. Both synergy and trade-off relationships are equally divided into five classes. The classification standard is shown in Table 2.

(2) Spatial Autocorrelation Model

Bivariate spatial autocorrelation involves two variables, selecting one function as the explanatory variable and another as the explained variable. Comparative analysis reveals their spatial synergy/trade-off relationships. The local Moran's I index characterizes the specific locations where two functions cluster in the same region. Identical clustering areas (high-high and low-low clusters) exhibit spatial synergy relationships, while heterogeneous clustering areas (high-low and low-high clusters) exhibit spatial trade-off relationships. The calculation formula is:

$$I_i = \frac{(X_y - \bar{X}_y) \sum_{j=1}^{n} \omega_{ij} (X_z - \bar{X}_z)}{\sigma_y^2 \sigma_z^2}$$

where I_i is the local Moran' s I index for region i; X_y is the attribute value y of spatial unit a; X_z is the attribute value z of spatial unit b; ω_{ij} represents the contiguity weight matrix; σ_y^2, σ_z^2 represent the variances of attribute values y and z; $\bar{X}_y$, $\bar{X}_z$ represent the mean values of attribute values y and z for all spatial units.

2 Spatio-temporal Differentiation Characteristics of Territorial Spatial Function Evolution

Using 1990, 2000, 2010, and 2018 as observation points, production, living, and ecological function values are calculated for each period according to formulas (1) and (4) to analyze the evolution characteristics of territorial spatial functions.

2.1 Spatio-temporal Differentiation Characteristics of Production Function

The mean production function values for each period are 0.21, 0.28, 0.35, and 0.41, respectively, showing an upward trend. Some banner counties exhibit fluctuating upward stage characteristics. From the natural breakpoint spatial differentiation of production function across periods (Figure 3), production function demonstrates a circular/semi-circular pattern centered on municipal districts with decreasing gradients outward. In 1990, production function high-value areas were distributed in strips; by 2000, a tripartite development pattern of production function advantage areas emerged, with regional production function improving rapidly. The gap between high and low production function areas gradually widened, with high-value areas' leading role strengthening further, while low-value areas with poor resource endowments showed obvious development "shortcomings" and lacked capacity to enhance overall production. In 2010, regional development strategies adjusted, with Ordos City focusing on building a modern green energy and chemical base, causing production function in some banner counties to decline, indicating that industrial structure optimization and adjustment achieved results and production function development became more rational.

[Figure 2: see original paper] [Figure 3: see original paper]

2.2 Spatio-temporal Differentiation Characteristics of Living Function

The mean living function values for each period are 0.19, 0.26, 0.36, and 0.48, respectively, showing an expansion trend significantly higher than production function. However, the urbanization effect of production function is the main driver of living function improvement. From the natural breakpoint spatial differentiation of living function across periods (Figure 4), living function also shows a circular pattern centered on municipal districts with outward gradient decrease. In 1990, living function high-value areas were distributed in Baotou City, Hohhot City, and their jurisdictions; by 2000, living function in surrounding banner counties began to improve; in 2010, living function advantage areas expanded rapidly in planar form, showing a similar center-periphery pattern to production function. By 2018, living function high-value areas remained basically stable in municipal districts, but living function advantage areas failed to form spatial cluster effects, indicating that most banner counties still need to improve their living function levels.

[Figure 4: see original paper]

2.3 Spatio-temporal Differentiation Characteristics of Ecological Function

The mean ecological function values for each period are 0.58, 0.55, 0.52, and 0.49, respectively, showing an overall declining trend. From the natural breakpoint spatial differentiation of ecological function across periods (Figure 5), ecological function clustering exhibits scale-dependent effects of natural landscapes. In 1990, ecological function high-value areas were concentrated in the central Yinshan Mountains, northern Yinshan foothills, and Ordos desert grassland areas; disadvantage areas were mainly in eastern Tumochuan Plain, northwestern and southern Ordos Plateau, with this spatial differentiation becoming more pronounced by 2000. In 2010, ecological function advantage areas in Baotou City and its jurisdictions declined significantly, with ecological function high-value areas mainly concentrated in the central Yinshan Mountains and northern foothills, the middle Ordos Plateau, and the Loess Plateau soil and water conservation area, showing no obvious advantages in other areas. In 2018, ecological function degraded overall, directly related to increased human disturbance intensity.

[Figure 5: see original paper]

3.1 Spatio-temporal Differentiation Characteristics of Synergy/Trade-off Relationships of Territorial Spatial Functions

Based on formulas (5) and (6), the coupling coordination degree of territorial spatial functions is calculated, with spatial distribution of coupling types shown in Figure 6. Overall, the coupling coordination degree of each banner county's territorial spatial functions shows an upward trend from 1990 to 2018, with obvious spatio-temporal differentiation.

In 1990, the coupling coordination degree ranged between 0.31-0.54. During this period, production and living functions were at low levels while ecological function had a good foundation, resulting in poor overall coupling coordination. Synergy relationships were concentrated in southern Baotou City jurisdictions, while trade-off relationships were dominated by mild imbalance. Critical imbalance was mainly distributed in Hohhot City and its jurisdictions and Tumote Left Banner, indicating both a good cooperation foundation and Hohhot City's development vision toward the west.

In 2000, the coupling coordination degree ranged between 0.32-0.56, with no change in coupling coordination types. The quantity ratio of trade-off to synergy relationships remained unchanged, with synergy relationships failing to serve as regional development drivers. Critical imbalance areas in Tumochuan Plain became contiguous, with geographical location advantages emerging. Additionally, Dongsheng District, Otuoke Banner, Otuoke Front Banner, and Wushen Banner showed a contiguous trend of critical imbalance, with initial regional cooperative development.

In 2010, the coupling coordination degree ranged between 0.39-0.71, with obvious regional polarization effects in synergy/trade-off relationships. Spatially, synergy distribution changed little. New polarization centers for primary coordination emerged in synergy relationships, while trade-off relationships formed four contiguous regions: northern Yinshan foothills trade-off area, Loess Plateau soil and water conservation trade-off area, northwestern Ordos Plateau trade-off area, and southern underdeveloped trade-off area. These trade-off relationships resulted from insufficient development momentum and increasingly tight ecological constraints, with intensified antagonism between economic development and environmental protection.

In 2018, the coupling coordination degree further improved, ranging between 0.41–0.71. Spatially, synergy relationships were widely distributed but mainly at barely coordinated levels; primary coordination and above levels were mainly in Hohhot City jurisdictions and Baotou City jurisdictions. Critical imbalance in trade-off relationships was mainly distributed in northern Yinshan foothills and Loess Plateau edge areas, primarily because these banner counties rely on natural foundations for development. With single industrial structures or insufficient momentum, production function lacks global driving capacity, living function development lags, and ecological function lacks regulation and restoration capacity, resulting in low coupling coordination levels.

[Figure 6: see original paper]

3.2 Spatial Coupling Characteristics of Synergy/Trade-off Relationships of Territorial Spatial Functions

To further analyze the spatial heterogeneity of synergy/trade-off relationships, bivariate spatial autocorrelation indices of production-living, production-ecological, and living-ecological functions are calculated using GeoDa software according to formula (7), with clustering results shown in Figure 7. Overall, production-living function synergy/trade-off relationships show significant spatial distribution clustering effects; production-ecological function synergy/trade-off relationships tend toward dispersion; living-ecological function synergy/trade-off relationships show spatial distribution convergence with production-ecological functions. The overall spatial coupling effect of synergy/trade-off relationships remains at a low level.

Specifically, the global Moran' s I indices for production and living functions are both positive from 1990 to 2018, indicating positive spatial correlation—high (low) production function values neighbor high (low) living function values. Locally, synergy relationships exist only as high-high clusters, while trade-off relationships exist as high-low and low-high clusters. The global Moran' s I indices for production and ecological functions are negative, indicating high (low) production function values neighbor low (high) ecological function values. Locally, both synergy and trade-off types exist. The global Moran' s I indices for living and ecological functions are also negative, indicating high (low) living function values neighbor low (high) ecological function values. Locally, synergy relationships show high-high and low-low clusters, while trade-off relationships show only low-high clusters.

[Figure 7: see original paper]

4 Discussion

Production and living functions in the Hohhot-Baotou-Ordos region continue to expand, while ecological function continues to decline. Production function remains in the factor-driven and scale expansion stage with low intensive utilization. Territorial spatial function development must strictly limit the compression of ecological function due to production function expansion. This study' s understanding of regional territorial spatial dominant function development patterns aligns with related scholars: territorial spatial functions overall show fluctuating production and ecological functions and expanding living functions. This is because resource-rich areas have cyclical production and processing patterns that create both positive and negative effects on ecological function, while living function continuously improves with construction land expansion and urbanization advancement. Although living function is expanding, gaps exist between living and production functions in most banner counties. If ecological function disturbance occurs, it will hinder regional sustainable development. Moreover, territorial spatial utilization has been extensive in recent years, with prominent regional ecological problems. Against a background of increasingly tight resource and environmental constraints, achieving high-quality development oriented toward ecological priority and green development has become critical, urgently requiring the construction of a new pattern of high-quality territorial spatial development and protection.

Therefore, future research can optimize territorial spatial development patterns based on evaluations of resource-environment carrying capacity and territorial spatial development suitability. Additionally, territorial spatial function identification under big data applications should be deepened to enable differentiated and intensive control of territorial space. Based on conclusions and the study area' s actual conditions, this paper proposes several targeted development suggestions:

(1) **For the Hohhot-Baotou area:** As an important agricultural and pastoral production base, it should develop an integrated land-use model combining agriculture and animal husbandry with ecological cycling. As an important base for energy processing, equipment manufacturing, and emerging industries, it should continuously adjust industrial structure layouts to safeguard industrial development needs. For living function, the radiating role of the two cities should be fully leveraged to create diverse and livable urban spaces with improved service functions and carrying capacities. For ecological function, priority should be given to controlling desertified cultivated land, restoring degraded grasslands, and optimizing water resource utilization.

(2) **For central Ordos area:** Given severe land salinization, water-saving agriculture should be vigorously promoted to improve irrigation water use efficiency. With prominent coal resource endowments, efficient and limited resource development should be ensured to promote intensive energy

resource processing. Urbanization started late but developed rapidly, so development of small and medium-sized towns can be advanced relying on Ordos City' s status as a provincial sub-center. Ecologically, this area faces patch fragmentation, mine restoration, and grassland degradation, requiring comprehensive promotion of green mine construction.

(3) **For western and southern Ordos area:** Livestock production function should be fully developed while strictly controlling grassland carrying capacity. Living environment quality is generally low, so characteristic towns can be encouraged and rural-pastoral settlement environment improvement can be implemented. Ecologically, the area should give full play to desert grassland ecosystem functions and reduce human interference in deserts and sandy lands.

(4) **For northern Yinshan foothills area:** Agricultural and pastoral production should focus on developing characteristic products and actively promoting conversion of cropland to forest and grassland. With outstanding industrial-mining production potential, rare earth mining layouts should be rationally arranged to cultivate innovative enterprise growth poles. For living function, Baiyun Obo should build a modern town suitable for living and working. Ecologically, the area has a fragile ecological foundation, requiring strengthened grassland protection and restoration of grassland ecosystem functions.

For the overall problem of declining ecological function, strong natural dependence, and low spatial synergy effect levels of territorial spatial functions, the study area should accelerate transformation of economic development patterns, promoting high-quality development models featuring ecological protection, green production, and low-consumption living. Territorial spatial use control is an important tool for macro regulation and micro management of territorial space. Therefore, protection and restoration can be achieved through constructing ecological security patterns (building ecological security networks, systematic governance of mountains, waters, forests, farmlands, lakes, grasslands, and deserts). Coordinated regional functional patterns require cooperation among banner counties in ecological co-development, industrial division of labor, and infrastructure to promote regional integration and narrow internal gaps.

5 Conclusions

This paper analyzes the evolution characteristics of territorial spatial functions in the Hohhot-Baotou-Ordos region and evaluates the synergy/trade-off relationships in functional evolution based on coupling coordination degree and bivariate spatial autocorrelation models. The main conclusions are:

(1) From 1990 to 2018, territorial spatial functions in the Hohhot-Baotou-Ordos region showed significant spatio-temporal differentiation characteristics. Production function in all banner counties was in an expansion

state, with spatial distribution presenting a circular/semi-circular pattern centered on municipal districts with outward gradient decrease. Living function expansion intensity was significantly higher than production function, with high values also concentrated in municipal districts, showing a similar circular distribution pattern. Ecological function continued to decline, with spatial clustering exhibiting scale-dependent effects of natural landscapes.

(2) The synergy/trade-off relationships of territorial spatial functions showed obvious spatio-temporal differentiation characteristics. The coupling coordination degree of territorial spatial functions in each banner county was on an upward trend, with the number of banner counties showing synergistic relationships increasing, but the overall level remained low. Production-living function synergy/trade-off relationships showed significant spatial clustering effects; production-ecological function synergy/trade-off relationships tended toward dispersion; living-ecological function synergy/trade-off relationships showed spatial distribution convergence with production-ecological functions. The spatial coupling effect of synergy/trade-off relationships among various functions was at a low level overall.

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