Spatiotemporal Evolution Characteristics and Influencing Factors of Production-Living-Ecological Spaces in the Farming-Pastoral Ecotone: A Case Study of Hohhot City, Inner Mongolia (Postprint)

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Abstract

The farming-pastoral ecotone is a crucial ecological security barrier and grain production base in northern China. Investigating the evolution patterns and influencing factors of its "production-living-ecological" space holds significant importance for territorial spatial optimization and sustainable development in ecologically fragile regions. This study employs methods including land use dynamic degree, land use transfer matrix, and Geodetector to examine the evolution characteristics and influencing factors of the "production-living-ecological" space in Hohhot City, a typical farming-pastoral ecotone in Inner Mongolia, from 2000 to 2020. The results indicate: (1) During the study period, the overall dynamic change of Hohhot City's "production-living-ecological" space was relatively gentle (0.02%~0.04%), with ecological, agricultural production, and pastoral production spaces showing a decreasing trend, while living and other production spaces increased. (2) From 2000 to 2020, the spatial pattern of Hohhot City's "production-living-ecological" space changed significantly, primarily manifested as living space encroaching upon agricultural and pastoral production spaces in urban peripheries, and mutual conversion among agricultural production, pastoral production, and ecological spaces in the Tumochuan Plain and the hilly regions of the north and southeast. (3) In the study area, ecological, agricultural production, and pastoral production spaces experienced intense mutual conversion during the first 10 years, which moderated from 2010 to 2020; living and other production spaces exhibited a net transfer-in status and surged during the latter 10 years. (4) Average slope is the dominant factor influencing the layout of agricultural and pastoral production spaces (0.24~0.4), while industrial development, human activities, and agricultural production scale exert

substantial impacts on the local spatial pattern. Under the context of refined governance, the role of policy guidance is becoming increasingly prominent.

Full Text

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Abstract

The farming-pastoral ecotone is an important ecological security barrier and grain production base in northern China. Exploring the evolution patterns and influencing factors of production-living-ecological spaces in ecologically fragile areas is crucial for territorial spatial optimization and sustainable development. This study employs land use dynamic degree, transfer matrix, and geographical detector methods to analyze the spatiotemporal evolution characteristics and influencing factors of production-living-ecological spaces in Hohhot, a typical farming-pastoral ecotone in Inner Mongolia, from 2000 to 2020. The results show that: (1) During the study period, the overall dynamic changes of production-living-ecological spaces in Hohhot were gentle (0.02%~0.04%), with ecological, agricultural production, and pastoral production spaces decreasing, while living and other production spaces increased; (2) From 2000 to 2020, the spatial patterns of production-living-ecological spaces in Hohhot changed significantly, mainly manifested as living space encroaching on agricultural and pastoral production spaces in the urban periphery, and mutual conversion among agricultural production, pastoral production, and ecological spaces in the Tumochuan Plain and its northern and southeastern hilly areas; (3) The ecological, agricultural production, and pastoral production spaces in the study area experienced intense mutual conversion in the first decade, with average slope being the dominant factor affecting the layout of agricultural and pastoral production spaces (0.24~0.4). Industrial development, human activities, and agricultural production scale have significant impacts on local spatial patterns, and the role of policy guidance is increasingly prominent under refined governance.

Keywords: production-living-ecological space; spatiotemporal evolution; influencing factors; farming-pastoral ecotone; Hohhot; Inner Mongolia

1 Introduction

Since 2000, rapid urbanization and industrialization have advanced in China, with the urbanization rate increasing from 17.6% to 64.72%. Urban population expansion has intensified land resource development and utilization, and increasingly diverse land function demands have led to intense conflicts among production, living, and ecological spaces within limited territorial areas [], with spatial dysfunction seriously constraining high-quality urban-rural development []. Studying the evolution characteristics and influencing factors of production-living-ecological spaces is beneficial for understanding land use development mechanisms and is significant for constructing a coordinated development pattern of production-living-ecological spaces and improving the territorial spatial governance system.

Production-living-ecological spaces are important carriers for human production, living activities, and ecological civilization construction. The three types of spaces, oriented by primary functions, coexist, integrate, and mutually constrain each other. Current research mainly focuses on concept definition and element identification [], function measurement and coupling relationships [], evolution characteristics and influencing factors [], and spatial optimization and development strategies []. Pattern evolution, as an important representation of human-land relationship interactions, has received increasing attention, gradually forming a research framework of "classification system construction - pattern evolution analysis - influencing factor identification - optimization strategy formulation". Some scholars have constructed classification systems for production-living-ecological spaces using methods such as index quantification, land use reclassification, and functional grading [], and conducted in-depth research on directions such as spatial evolution and ecological environmental effects [], influencing factors, and optimization strategies []. Overall, existing research covers scales from national, urban agglomerations, provinces and cities to counties, towns, and characteristic zones, but pays less attention to farming-pastoral ecotones with fragile habitats and significant spatial heterogeneity. Most researchers explore the mutual transformation relationships among production-living-ecological spaces based on dominant land functions, lacking targeted classification and in-depth research on specific areas.

The farming-pastoral ecotone is an ecologically fragile zone bordering pastoral and agricultural areas, characterized by interwoven agricultural and pastoral spaces and alternating production activities, making it a key focus of human-land relationship research []. With socio-economic development and the implementation of ecological protection policies, various elements in farming-pastoral transitional areas such as Hohhot are constantly reorganizing, with tense human-land relationships and intense competition among production-living-ecological land uses []. Desertification and grassland degradation occur frequently, making understanding the spatial evolution patterns and driving mechanisms an important proposition for achieving social-ecological sustainable development in the region. Therefore, this study takes Hohhot as an example to construct

a production-living-ecological space classification system that conforms to the development characteristics of farming-pastoral ecotones, and uses dynamic degree models, transfer matrices, and geographical detectors to explore the evolution characteristics and influencing factors of production-living-ecological spaces in the Inner Mongolia farming-pastoral ecotone, aiming to enrich land use research in areas with significant spatial heterogeneity and provide a basis for local production-living-ecological space optimization strategies.

1.1 Study Area Overview

Hohhot is located in the middle section of the farming-pastoral ecotone in northern China, covering an area of 1.72$×10^{4}$ km^2, with jurisdiction over 4 districts, 4 counties, and 1 banner. In 2020, the city's total population reached 3329.1$×10^{4}$ people, with a regional GDP of 355.11$×10^{8}$ yuan. The territory presents a landform characteristic of "one mountain, one plain, and two hilly areas", with the Daqing Mountains in the north-central part, the Tumochuan Plain in the central part, and interlaced hilly areas in the north and southeast, which has established the foundation for the region's integrated agricultural and pastoral industrial development. However, the long-standing practice of "emphasizing agriculture over animal husbandry, and production over ecology" has made the area a typical wind-eroded desertification zone and ecologically fragile region [], making the study of its production-living-ecological space evolution characteristics and driving factors highly representative.

1.2 Data Sources

The classification data of production-living-ecological land use in Hohhot from 2000 to 2020 were obtained from the Resources and Environmental Sciences and Data Sharing Platform of the Chinese Academy of Sciences. The data were primarily generated based on Landsat 8 remote sensing image interpretation (resolution 30m), using the land resource classification system standard of the Chinese Academy of Sciences. Elevation, slope, and aspect data for natural factors were obtained from the Geospatial Data Cloud; precipitation and temperature data were sourced from the China Meteorological Elements Annual Spatial Interpolation Dataset; socio-economic factors were obtained from the Hohhot Statistical Yearbook (2000-2020).

1.3 Research Methods

1.3.1 Construction and Scoring of Production-Living-Ecological Space Classification System The construction of a production-living-ecological space classification system is fundamental to spatial evolution analysis. Focusing on the spatial heterogeneity of agricultural-pastoral mixing and the current development issues of imbalanced agricultural-pastoral structure in the study area [], and based on the dominant function approach to delineate production-living-ecological spaces [], this study references the ideas of Zou Linlin et al. [] and Liu Pinghui et al. [] to further divide

production space into three categories: agricultural, pastoral, and other production spaces (forestry, fishery, secondary industry, tertiary industry), to deeply explore the internal evolution relationships of agricultural and pastoral land. Simultaneously, considering the functional complexity of spaces and referencing the functional hierarchy division by Liu Jilai et al. [], Wang Shiqing et al. [], and Zhai Yujuan et al. [], as well as existing research scoring results for production-living-ecological spaces in farming-pastoral ecotones, a six-level scoring principle was adopted to describe the primary-secondary and strong-weak relationships of various spatial functions. The classification and scoring system linking production-living-ecological spaces with land use categories in the farming-pastoral ecotone was constructed (Table 1), providing a foundation for subsequent analysis of functional score changes and high-value area patterns. Among them, cultivated land has agricultural production as its primary function, can serve as temporary pasture in winter, has weak pastoral production land characteristics, and simultaneously plays a semi-ecological role; forest land is primarily ecological with weak production functions, and other forest land has weak agricultural and weak pastoral production land characteristics; grassland is primarily ecological with pastoral production land characteristics, and different types of grassland are assigned values based on vegetation coverage.

1.3.2 Land Use Dynamic Degree The land use dynamic degree model can quantitatively characterize the rate and intensity of spatial dynamic changes []. A single dynamic degree was used to describe changes in various production-living-ecological spaces in Hohhot. The formula is:

$$D = \frac{S_b - S_a}{S_a} \times 100\%$$

where D is the dynamic degree of a certain space; a and b represent the study periods; S_a and S_b are the areas of the space in periods a and b, respectively.

A comprehensive dynamic degree was used to describe the overall change intensity of production-living-ecological spaces in Hohhot. The formula is:

$$DC = \frac{\sum_{i,j} |\Delta LS_i|}{\sum_i LS_i} \times 100\%$$

where DC is the comprehensive dynamic degree; a and b represent the study periods; ΔLS_i represents the absolute area of space i converted to space j; LS_i is the area of space i in period a; and $b - a$ is the study period.

1.3.3 Land Use Transfer Matrix The land use transfer matrix can quantitatively characterize the change characteristics and transfer directions of production-living-ecological spaces []. Map algebra tools were used to obtain the mutual transfer conditions of production-living-ecological spaces in

corresponding periods. The expression is:

$$P_{ij} = \begin{bmatrix} P_{11} & \cdots & P_{1n} \\ \vdots & \ddots & \vdots \\ P_{n1} & \cdots & P_{nn} \end{bmatrix}$$

where P_{ij} represents the area converted from space i to space j; n represents the number of production-living-ecological space types.

1.3.4 Geographical Detector Geodetector is a statistical tool for analyzing the stratified heterogeneity of research objects and measuring the influence of driving factors on spatial differentiation using q-values [], where explanatory power increases with larger q-values []. This study selected differentiation and factor detectors to analyze the driving effects of natural and socio-economic factors X on the area changes Y of various production-living-ecological spaces in the study area. The expression is:

$$q = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N\sigma^2}$$

where L is the stratification of socio-economic factor X; N_h and N are the number of units in stratum h and the entire region, respectively; σ_h^2 and σ^2 are the variances of Y values in stratum h and the entire region, respectively.

2 Results and Analysis

2.1 Evolution Characteristics of Production-Living-Ecological Spaces

2.1.1 Dynamic Evolution Characteristics From 2000 to 2020, the comprehensive changes in production-living-ecological spaces in Hohhot were relatively gentle, with comprehensive dynamic degrees mostly between 0.02% and 0.04%. The period 2010-2015 had the most drastic comprehensive dynamic change, far exceeding other periods (0.08%), mainly caused by sudden increases in living space and other production spaces. During the study period, ecological, agricultural production, and pastoral production spaces showed decreasing trends with mostly negative single dynamic degrees, while living and other production spaces showed expansion trends with mostly positive single dynamic degrees. From 2000 to 2005, urban population surged, and living space and other production spaces experienced expansion peaks, with single dynamic degrees reaching historical maximums (1.27% and 0.78%, respectively), continuously encroaching on ecological space and agricultural/pastoral production spaces (Table 2).

2.1.2 Spatial Pattern Evolution Characteristics The classification and scoring results of production-living-ecological spaces were reclassified and visualized to obtain the spatial distribution maps of production-living-ecological spaces in Hohhot from 2000 to 2020 (Figure 1). Using the natural breaks

classification method, the evolution characteristics were described as stable, contracted, or expanded (Figure 2). The production-living-ecological spaces in Hohhot are distributed according to local conditions: high-value areas of agricultural production space are mainly concentrated in the Tumochuan Plain and the northern hilly areas of Wuchuan County with flat terrain and excellent hydrogeological conditions (Figure 1a); high-value areas of pastoral production space are concentrated in Wuchuan County and the southern hilly areas (Figure 1b); living space shows a layout characteristic of "large agglomeration, small dispersion," with highly concentrated large patches in Hohhot urban area, certain agglomeration effects in county towns, and scattered distribution in towns and natural villages (Figure 1d); high-value areas of ecological space are mainly concentrated along the Daqing Mountains and the Manhan Mountain hills in the southeast, forming an important ecological security barrier for the Tumochuan Plain (Figure 1c). With rapid socio-economic development, high-value areas of other production spaces such as factories, mines, and large industrial zones are distributed in scattered points in the southern urban area and southern Tumote Left Banner, gradually expanding (Figure 1e).

From 2000 to 2020, the spatial patterns of production-living-ecological spaces in Hohhot changed significantly: mainly manifested as agricultural and pastoral production spaces in hilly areas of Wuchuan County and Helingeer County being converted to ecological space under the guidance of the Grain for Green policy; living space encroaching on agricultural and pastoral production spaces around Hohhot urban area driven by rapid urbanization; low-scoring ecological spaces such as beach land and saline-alkali land in the Tumochuan Plain being converted to agricultural production space and other production space (mainly other construction land) driven by land reclamation and improvement projects; and forest land in southern Helingeer County degrading to pastoral grassland under the influence of overgrazing and soil erosion, enhancing pastoral production functions while weakening ecological functions (Figure 2).

The spatial pattern is comprehensively affected by natural, socio-economic, and policy factors []. This study uses factor detection tools to quantitatively analyze the impacts of natural and socio-economic factors on the evolution of production-living-ecological spaces in the study area. Referencing existing research results [], five natural factors including average slope (X1), aspect (X2), average elevation (X3), annual rainfall (X4), and average annual temperature (X5), and nine socio-economic factors including population density (X6), urbanization rate (X7), per capita disposable income of farmers and herders (X8), primary industry output value (X9), secondary industry output value (X10), tertiary industry output value (X11), total output value of agriculture, forestry, animal husbandry, and fishery (X12), total grain output (X13), and total meat output in the current year (X14) were selected as independent variables, with the area of production-living-ecological spaces in different periods in Hohhot as dependent variables for detection. All results passed significance tests ($P<0.05$). Policy factors were analyzed qualitatively as they are difficult to quantify.

2.1.3 Land Use Transfer Characteristics Transfer matrix results show (Table 3): From 2000 to 2010, ecological space and agricultural/pastoral production spaces experienced intense mutual conversion. Ecological space was mainly converted to agricultural production space (269.96 km^2) and pastoral production space (279.40 km^2); the mutual conversion area between agricultural and pastoral production spaces was 279.52 km^2; living space and other production spaces showed net inflow, increasing by 88.92 km^2 and 17.85 km^2, respectively. This indicates that ecological space was squeezed during this period, with prominent contradictions between cultivated land and grassland and serious waste of land resources. From 2010 to 2020 (Table 3): The mutual conversion between ecological space and agricultural/pastoral production spaces slowed down compared to the previous decade; net inflow areas of living space and other production spaces increased substantially, leading to increasingly tense human-land relationships.

2.2 Influencing Factor Analysis

2.2.1 Natural Factors Factor detection results show (Table 4): Natural factors have the most significant impact on pastoral production space and relatively less impact on ecological space. Average slope and annual rainfall determine terrain complexity and nourishment levels for aboveground organisms, being high-level natural factors affecting the evolution of agricultural production space, pastoral production space, and living space. Among them, average slope has the greatest explanatory power for pastoral production space ($q=0.40$ in 2000). Average annual temperature has weak explanatory power for all types of spaces ($q<0.10$). From a temporal perspective, as spatial location and land use structure become relatively stable, the explanatory power of natural factors on the spatial patterns of production-living-ecological spaces in the study area has weakened.

2.2.2 Socio-Economic Factors Factor detection results show (Figure 3): Compared with natural factors, socio-economic factors have more significant impacts on the evolution of production-living-ecological spaces in the study area. The total output value of agriculture, forestry, animal husbandry, and fishery, primary industry output value, and urbanization rate are the dominant factors for the evolution of agricultural production space; secondary industry output value, total grain output, and per capita GDP are the dominant factors for pastoral production space evolution; secondary industry output value, total output value of agriculture, forestry, animal husbandry, and fishery, and primary industry output value are the dominant factors for other production space evolution; population density, tertiary industry output value, and urbanization rate are the dominant factors for living space evolution; total grain output, secondary industry output value, and primary industry output value are the dominant factors for ecological space evolution. In summary, different types of spaces have different dominant evolution factors, but factors such as primary

and secondary industry output values, urbanization rate, total output value of agriculture, forestry, animal husbandry, and fishery, and total grain output have strong explanatory power for the evolution of production-living-ecological spaces in the farming-pastoral ecotone, indicating that industrial development, human activities, and agricultural production scale have significant impacts on the spatial distribution patterns of the region. Notably, agricultural production scale has significant impacts on both pastoral production space and ecological space. From a temporal perspective, the explanatory power of socio-economic factors on living space has gradually increased, while their explanatory power on other spaces has decreased.

2.2.3 Policy Factors Inner Mongolia holds a prominent position in China's "Two Screens and Three Barriers" ecological security pattern and is an important territory for ecological civilization construction. Since 2000, China has vigorously promoted the "Grain for Green" and "Pasture Restoration" policies to restore the ecological environment. In the northern part of Wuchuan County and Helingeer County, these policies have achieved initial success in ecological space restoration. During the 13th Five-Year Plan period, the Autonomous Region's Department of Agriculture and Animal Husbandry proposed implementing grain-forage rotation and returning farmland to grassland policies in 4 farming-pastoral banner counties of Hohhot, promoting the alternating conversion of agricultural and pastoral production spaces in the study area. With further implementation of high-quality development concepts, basic farmland protection has received increasing attention, and projects such as saline-alkali land improvement have promoted the restoration of agricultural production spaces in the Tumochuan Plain. Meanwhile, the implementation of urbanization and Western Development strategies has enhanced the attractiveness of urban areas, with large populations flowing into the city. Under the guidance of the Hohhot Urban Master Plan (2011-2020), the urban area gradually formed a development pattern of "optimizing the east, expanding the south, connecting the west, and controlling the north," resulting in the replacement of peripheral agricultural and pastoral production spaces by living spaces. In summary, policy guidance has a significant impact on the evolution of production-living-ecological spaces in farming-pastoral areas.

3 Discussion

Taking Hohhot as an example, this study explores the evolution characteristics and influencing factors of production-living-ecological spaces in the Inner Mongolia farming-pastoral ecotone. Compared with existing research [], this study comprehensively considers the current status and development issues of agricultural-pastoral 复合现状 in the region, further subdivides production space into agricultural, pastoral, and other production spaces, and deeply analyzes the internal evolution relationships of agricultural and pastoral production land, broadening relevant research perspectives. Factors such as total grain output and total meat output in the current year were selected to characterize agri-

cultural and pastoral production scales, enhancing the pertinence of influencing factors.

The study found that from 2000 to 2020, living space in Hohhot urban area expanded significantly, while living space patches in county towns grew slowly and their agglomeration effects remain to be enhanced; agricultural production, pastoral production, and ecological spaces continued to decrease with frequent mutual conversions, highlighting the conflict between protection and development []. Therefore, Hohhot should enhance the radiation and driving role of the urban area, deliver talent to various banner counties, revitalize idle land in urban areas and banner counties, and improve land use efficiency of living and other production spaces. The Tumochuan Plain and hilly areas should implement graded and classified refined management according to spatial evolution characteristics, establishing forage-grain coupling production units in areas with frequent agricultural-pastoral production space conversion to vigorously develop forage industries and rotational farming, supporting sustainable "forage-grain" development; and establishing buffer units in areas undergoing land reclamation, improvement, and returning farmland to grassland to consolidate existing ecological protection achievements and prevent land degradation.

Regarding influencing factors, the evolution of production-living-ecological spaces is comprehensively affected by natural, socio-economic, and policy factors, similar to existing research findings []. Notably, agricultural production scale among socio-economic factors has significant impacts on both pastoral production space and ecological space, which is an important supplement to existing research findings and provides insights for planning managers to comprehensively consider the cross-effects of various activities when optimizing production-living-ecological spaces in farming-pastoral areas. Future research can adopt multiple influencing factor analysis methods to explore the positive and negative effects of factors and their interactions, simulate development trends of production-living-ecological spaces under different dominant factors, and propose corresponding optimization strategies.

4 Conclusions

This study comprehensively analyzes the evolution characteristics and influencing factors of production-living-ecological spaces in the Inner Mongolia farming-pastoral ecotone of Hohhot using land use dynamic degree models, transfer matrices, and geographical detector models. The main conclusions are:

(1) From 2000 to 2020, the overall dynamic changes of production-living-ecological spaces in Hohhot were gentle (0.02%~0.04%), with ecological, agricultural, and pastoral production spaces decreasing, while living and other production spaces increased. In the first decade, ecological, agricultural, and pastoral production spaces experienced intense mutual conversion, with ecological space having the largest transfer area and prominent contradictions between cultivated land and grassland. In the latter decade,

living and other production spaces suddenly increased, with increasingly severe encroachment on other spaces and tense human-land relationships.

(2) From 2000 to 2020, the spatial patterns of production-living-ecological spaces in Hohhot changed significantly, mainly concentrated in Hohhot urban area, the Tumochuan Plain, and the northern and southeastern hilly areas. Urban living space expanded rapidly following a pattern of "optimizing the east, expanding the south, connecting the west, and controlling the north," and subsequent development should revitalize idle land and enhance radiation driving effects on banner counties. The Tumochuan Plain and hilly areas should implement graded and classified refined management according to spatial evolution characteristics.

(3) Average slope is the dominant natural factor affecting the layout of agricultural and pastoral production spaces. Among socio-economic factors, industrial development, human activities, and agricultural production scale have high explanatory power, with agricultural production scale significantly affecting pastoral production space and ecological space. Except for living space, the explanatory power of natural and socio-economic factors on spatial pattern changes has weakened. Under the background of high-quality development, policy guidance is increasingly prominent for the coordinated development of production-living-ecological spaces.

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