Urban Land Use Transition and Eco-environmental Effects in the Farming-Pastoral Ecotone Based on "Production-Living-Ecological" Space: A Case Study of Baotou City (Postprint)

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Abstract

The land use transformation and ecological environment construction in the farming-pastoral ecotone constitute an important pillar for sustainable development in northwestern China. Based on the "production-living-ecological" space perspective, this study utilizes three-phase remote sensing data of Baotou City from 2000, 2010, and 2020, and employs methods including land transition matrix, ecological environment quality index, and ecological contribution rate to analyze the characteristics of land use transformation and its ecological environmental effects. The results indicate: (1) During the study period, the overall pattern of Baotou City's "production-living-ecological" space remained stable, with production and ecological land decreasing while living land continued to increase. Pasture ecological land experienced the largest area transferred out, followed by agricultural production land; urban living land and industrial-mining production land had the largest area transferred in. (2) From 2000 to 2020, Baotou City's ecological environment quality index declined, with values of 0.6292, 0.6208, and 0.6194, respectively; however, the improvement trend outweighed the deterioration trend. The area of high-quality ecological zones in the northern part of the city decreased; the medium-quality zone in the central part slowly diminished, while the low-quality zone in the southern part continued to increase toward the southeast. (3) The occupation of pasture ecological land generated significant negative ecological environmental effects, whereas the conversion of other ecological land and agricultural production land to pasture ecological land represented the dominant factor in ecological environment improvement. Through studying the land use transformation and its ecological environmental effects in Baotou City, this research aims to provide references for optimizing the "production-living-ecological" space and protecting the ecological environment in cities within the farming-pastoral ecotone.

Full Text

Preamble

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Analysis of Urban Land Use Transformation and Ecological Environment Effects in Agro-Pastoral Transitional Zones Based on "Ecological-Production-Living" Spaces: A Case Study of Baotou City

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Abstract: The transformation of land use and ecological environment construction in agro-pastoral transitional zones serves as an important foundation for sustainable development in northwestern China. Based on the perspective of ecological-production-living spaces and using remote sensing data from Baotou City for the years 2000, 2010, and 2020, this study analyzes the characteristics of land use transformation and its ecological environment effects through methods including land transfer matrix, ecological environment quality index, and ecological contribution rate. The results indicate that: (1) The overall pattern of Baotou's ecological-production-living spaces remained stable during the study period, with production and ecological land decreasing while living land continuously increased. Grassland ecological land experienced the largest transfer-out area, followed by agricultural production land; urban living land and industrial production land showed the largest transfer-in areas. (2) From 2000 to 2020, Baotou's ecological environment quality index declined from 0.6292 to 0.6208 and 0.6194, but the improvement trend outweighed the deterioration trend. The high-quality ecological zone area in the city's northern region decreased; medium-quality zones in the central region slowly diminished; and low-quality zones in the southern region continued to expand southeastward. (3) The negative ecological effects from occupying grassland ecological land were significant, while the conversion of other ecological land and agricultural production land into grassland ecological land constituted the dominant factor for ecological environment improvement. This study of Baotou's land use transformation and ecological environment effects aims to provide references for optimizing ecological-production-living spaces and protecting the ecological environment in urban agro-pastoral transitional zones.

Keywords: ecological-production-living spaces; land use function transformation; ecological environment effect; agro-pastoral ecotone; Baotou City

Introduction

Since the reform and opening-up, accelerating urbanization has intensified the transformation of urban and rural spaces, triggering land use structure imbalances and exacerbating habitat problems such as soil desertification and biodiversity loss. China is currently in a critical period of high-quality transformation development. The 18th National Congress report established the principle of intensive and efficient production spaces, beautiful ecological spaces, and livable living spaces. Land use transformation, as a concrete manifestation of socio-economic development stage transitions, correlates with the concepts of production, ecological, and living functions, offering a new perspective for exploring ecological environment effects under multifunctional land use transformation. This perspective holds practical significance for systematically understanding regional ecological environment quality and changes and optimizing land resource allocation.

The concept of land use transformation emerged from Grainger's forest transition hypothesis, corresponding to the developmental stage transition of land use morphology driven by regional socio-economic transformation and innovation. This involves land transformation theory, urban-rural development relationships, and land use analysis under different functional divisions. Scholars such as Long Hualou have studied land use transformation characteristics conforming to China's socio-economic features, exploring internal dynamic mechanisms, patterns, manifestations, and effects. Among these, the ecological environment effects of land use transformation represent an important entry point for studying national territorial space environmental changes and the foundation for future rational land use structure transformation. Existing research has examined land use transformation and its relationship with ecological environment through natural and socio-economic approaches, providing references for this study. Methods such as land use transfer matrix and dynamic degree have been used to analyze structural transformation, quantity proportions, and centroid shifts, while models including InVEST, landscape ecological pattern indices, and spatial econometric regression have been employed to analyze ecosystem service value evaluation systems across various regions. Studies have also measured impacts on biodiversity reduction and habitat fragmentation, investigated habitat quality of different land use types, and explored habitat pattern evolution, dynamic mechanisms, and regional characteristics.

Current research on land use transformation and ecological environment effects in China's characteristic regions includes studies on the Yangtze River Delta region, valley cities, the Qinling area, and various administrative scales. However, research on northwestern cities is lacking, particularly for agro-pastoral transitional zone cities characterized by overlapping land functions, fragile ecological environments, and heavy responsibilities for ecological protection. The agro-pastoral ecotone represents a population concentration center within ecological transition zones and agricultural production marginal zones, where ecological environments experience the most profound external interference. Since

implementing comprehensive grazing prohibition and other ecological conservation policies, certain achievements have been made, but problems such as land use patterns constraining benign ecological development and the separation between land use planning and ecological environment impact research urgently require solutions. As a typical ecologically sensitive area significantly affected by China's urbanization process, the impact of land use transformation on ecological environment has become a critical frontier for studying urban sustainable development.

Given this context, this paper takes Baotou City as a case study. Based on remote sensing data and spatial technology, it examines the spatio-temporal evolution characteristics of land use transformation and ecological environment effects from the ecological-production-living space perspective, analyzing Baotou's sustainable development priorities to provide decision-making references for coordinating limited land resource development and ecological civilization construction in agro-pastoral transitional zones.

2.1 Data Sources

The land use remote sensing monitoring data for Baotou City for the years 2000, 2010, and 2020 were obtained from the Resource and Environmental Science and Data Center of the Chinese Academy of Sciences. This dataset was interpreted using Landsat TM imagery as the primary information source with a resolution of 100 m.

By drawing upon the dominant function classification scheme for ecological-production-living land use transformation from Yang Qingke et al. , the study established 6 primary land categories and 25 secondary categories. Considering Baotou's socio-economic needs, multifunctional grassland was specifically classified. First, through analyzing the dominant functions of land use, grassland's functions were categorized into grassland ecological function and pastoral production function. Ecological functions include environmental regulation, livestock habitat, and information transfer, while production functions include forage material supply, raw material production, and pastoral space. Second, from an area proportion perspective, fenced grassland in Baotou accounts for 87.2% of total grassland area, with the remainder being grazing grassland. Since 2000, comprehensive fencing has been implemented, prioritizing ecological functions over production functions, which better aligns with sustainable development concepts. Therefore, grassland was classified as ecological land. Finally, based on the characteristics of agro-pastoral transitional zones and drawing upon the secondary land category ecological environment quality index established by Li Xiaowen et al., ecological environment quality values were assigned to Baotou's ecological-production-living land through area-weighted methods .

Baotou City is located in Inner Mongolia Autonomous Region, geographically positioned between 109°15 ~110°26 E and 40°15 ~42°43 N, with elevations ranging from 1067.2 m. It serves as an important industrial base in China. Due

to its fragile ecological environment, Baotou has adopted coordinated land use and ecological protection as a priority development strategy, resulting in a high urban livability index. The city comprises 6 districts, 3 agricultural and pastoral banners/counties, and 2 high-tech industrial development zones, covering a total area of 27768 km^2, with cultivated land of 4303 km^2 and grassland of 18686 km^2. The population totals 2.7 million, including 0.4 million agricultural and pastoral residents. Baotou features a semi-arid temperate continental monsoon climate with drought and frequent sandstorms throughout the year. The geomorphology is complex with diverse land types, sloping from northwest to southeast. The Yinshan Mountains traverse the city's central region, with the southern plain adjacent to the resource-rich upper Yellow River area featuring fertile soil that serves as the crop production zone and primary economic construction area. The eastern and western regions connect to the Tumochuan and Hetao Plains, while the northern region consists of plateau grasslands focused on industry and pastoralism. Under the influence of location, climate, and topography, Baotou has become a key city in China's northwestern agro-pastoral transitional zone.

2.2 Research Methods

This study employs a land use transfer matrix model to quantitatively describe the area and proportion information of land transfers, obtaining land use transfer data for three periods to analyze Baotou's land use function structure transformation and ecological-production-living space evolution characteristics. From an ecological perspective, the ecological environment quality index and ecological contribution rate are calculated to explore ecological conditions under land use transformation.

The ecological environment quality index model integrates land category ecological environment quality index, area, and ecological environment quality correlation to measure Baotou's overall habitat quality during the study period:

$$EV_t = \sum_{i=1}^{n} \frac{S_{ki}}{S_k} \times R_i$$

where EV_t represents the ecological environment quality index of ecological unit k in period t; S_{ki} is the area of land type i within ecological unit k in period t; S_k is the total regional area; n is the total number of land use types; and R_i is the ecological environment index of land type i.

The land use function transformation ecological contribution rate quantifies the ecological environment quality contribution of dominant function transformations, intuitively reflecting improvement and deterioration effects:

$$LEI = \frac{(LE_1 - LE_0) \times LA}{S_k}$$

where LEI is the ecological contribution rate of land function change (positive or negative); LE_1 and LE_0 are the ecological environment quality indices of changed land in the initial and final periods; LA is the changed area; and S_k is the total area of the ecological unit.

3.1 Land Use Function Structure Transformation

3.1.1 "Ecological-Production-Living" Spatial Pattern and Changes

Baotou's ecological-production-living spatial pattern remained relatively stable during the study period . Ecological space, dominated by grassland ecological land, covered the northern and central-southern regions in patches divided by the Yinshan Mountains, with a total area reduction of 267.40 km^2. Forest and water ecological land decreased by 54.59 km^2, while grassland ecological land reduction was controlled at 212.81 km^2, equivalent to 1.55 times the reduction in the first decade. Production space featured industrial production land scattered throughout the region and agricultural production land concentrated in the southern mountainous zone and northern Yellow River alluvial belt, interspersed with grassland ecological land on the northern plateau and southern plain of Yinshan. Industrial land increased by 271.38 km^2 with an average annual growth rate of 1.55%. Living space, the smallest area, concentrated in the southern urban region with flat terrain, developed industry, and concentrated agriculture. Influenced by rapid urbanization, urban living land continuously increased by 15.39 km^2, advancing southeastward at an average annual growth rate of 9.77%, 3.2 times the growth of rural living land, indicating significant disparities in urban-rural development levels.

From 2000 to 2020, Baotou experienced rapid industrial and mining development, accelerated urbanization construction, increased living space demand, and certain impacts on ecological space. The grain-for-green policy showed initial effects, curbing ecological land degradation and development occupation.

3.1.2 "Ecological-Production-Living" Spatial Land Use Transformation Analysis

The study obtained land use status for three periods in Baotou and derived land use transfer matrices [Figure 1: see original paper] to explore land conversion patterns based on ecological-production-living spaces, providing a data foundation for ecological environment impact research.

Production Land: Agricultural production land transferred out significantly, primarily converting to urban living land (122.10 km^2) and forest ecological land (51.01 km^2) during 2000-2010 due to its flat terrain and proximity to urban areas. During 2010-2020, it mainly transferred to grassland ecological land (111.47 km^2) and industrial production land (146.58 km^2), corresponding to the economic development stage emphasizing heavy industry, with rapid industrial land increase.

Ecological Land: Grassland ecological land experienced the most overall flow, primarily transferring to production land, though the degradation trend gradually eased. Newly added forest land mainly came from grassland ecological land (97.70 km^2). During 2010-2020, other ecological land showed the largest transferred-in area (120.40 km^2), with agricultural land having the largest transferred-in area (149.21 km^2) under semi-intensive farming promotion and grain-for-green policy implementation. Water ecological land transferred in primarily from agricultural production land (45.49 km^2) and other ecological land (35.34 km^2). The proportion of other ecological land significantly influenced ecological construction direction, with continuous transfer-out indicating effective ecological governance measures and gradually improving ecological restoration capacity.

Living Land: Urban living land during 2000-2010 primarily came from agricultural production land (63.09%) and grassland production land (15.96%), with additional conversion from rural residential areas. Rural living land transfer-in area was relatively small, directly related to the loss of agricultural production and grassland ecological land. Grassland ecological land transferred out at a constant rate, while agricultural production land transfer-out accelerated significantly in the later period, 4.8 times the earlier rate, indicating that farmers' urbanization exceeded herdsmen's, with rapid initial growth followed by steady settlement acceleration for herdsmen.

With socio-economic development, the overall conversion trend showed ecological and production land transferring to living land. Agricultural production and grassland ecological land had the largest transfer-out areas, with functional exchange between them becoming the region's important land conversion pattern, demonstrating simultaneous phenomena of "returning farmland to grassland" and "grassland conversion to farmland." Land supply-demand contradictions persist in agro-pastoral transitional zone cities with ecological protection as the development bottom line, requiring further attention to the ecological environment impacts of these phenomena.

3.2 Ecological Environment Effects of "Ecological-Production-Living" Space Transformation

3.2.1 Ecological Environment Quality Index and Spatio-Temporal Evolution Analysis

Based on the formula, Baotou's ecological environment quality indices for 2000, 2010, and 2020 were calculated as 0.6292, 0.6208, and 0.6194 respectively, showing a declining trend but with improvement trends outweighing deterioration trends. The overall index decline cannot indicate unchanged ecological environment, as positive and negative effects from land type changes can offset each other. Using the natural breaks method, habitat quality was classified into four grades: low (<0.293), medium-low (0.293-0.521), medium-high (0.521-0.883), and high (>0.883) .

Baotou's high and medium-high quality ecological spatial patterns remained generally stable. High-quality zones decreased from 70.47% to 69.45%, composed of grassland and shrub forest, distributed in patches north of the city center, forming a high-quality ecological foundation for windbreak and sand fixation ecological function areas and serving as the southern Daqing Mountain ecological barrier. Medium-high quality zones increased slightly from 1.61% to 1.82%, composed of medium-coverage grassland, sparse forest, and water ecological land, forming transition zones interwoven with high-quality zones in central agro-pastoral areas and southern Yellow River zones.

Medium-quality zones decreased uniformly from 18.08% to 16.81%, distributed in belts along both sides of the Yinshan Mountains, primarily consisting of agricultural production land. Due to strict government regulation of mineral resource development and strengthened mine land reclamation measures, low-quality zone area growth slowed, increasing by 55.39 km^2, composed of industrial land and low-coverage grassland, sporadically growing in industrial zones on the northern plateau. The area in 2020 was 2.1 times that of 2000, with spatio-temporal changes closely related to urban construction, evolving from scattered point growth to patchy dispersion, forming "low-quality expansion hotspots" centered on towns. Growth was evident in the southern central urban area and Baiyun Obo mining district, with multiple low-quality regional development nuclei emerging in the southeast. However, low-quality ecological patches in Damao Banner decreased significantly, benefiting from long-term measures for sand source control and species conservation.

3.2.2 Spatio-Temporal Analysis of Ecological Environment Effects from "Ecological-Production-Living" Space Transformation

The ecological environment quality of ecological-production-living spaces generates positive and negative effects with land type changes. Though overall indices remain stable, this doesn't indicate unchanged ecological environments. Based on the formula, quantitative analysis of key land type transformations' contribution rates during 2000-2020 shows that grassland ecological land transformation was the most important factor affecting ecological environment effects .

During 2000-2010, factors contributing significantly to positive ecological effects included: ecological governance achievements from converting other ecological land around industrial and mining areas to grassland ecological land (37.22%); large-scale conversion of agricultural production land (32.41%) and grassland ecological land (11.30%) to other types. Negative effects were mainly influenced by grassland ecological land transfer-out: conversion to industrial production land (37.67%) due to heavy industrial projects like Baotou Steel and Baiyun Obo mining area; conversion to other ecological land (15.37%) as secondary and tertiary industries developed rapidly and living needs increased; and conversion to rural living land (9.55%) due to rural construction in Bailingmiao Town.

During 2010-2020, grassland ecological land conversion remained the key factor:

conversion to industrial production land showed similar positive and negative effects (13.00% and 14.17%), with targeted governance of previously negative-effect land showing large positive contributions under green mine construction and mining clearance policies. Agricultural production land conversion contributed the second-largest effect (20.33%), with wide-ranging, high-density positive effects mainly located in central agro-pastoral belts and southern agricultural development zones. Positive contribution from rural living land conversion (11.08%) mainly stemmed from ecological restoration measures in Bailing Town in the early period, while negative contribution (8.22%) was affected by increased urban villages in the south. Conversion with other ecological land was scattered across the region with small unit areas, making comprehensive governance difficult, with positive and negative contribution rates of 13.51% and 9.55% respectively.

Overall, the conversion of other ecological land and agricultural production land to grassland, forest, and water ecological land produced important positive impacts (78.98%), with agro-pastoral land conversion contributing the largest and most sustained effect. Other ecological land actively converted to grassland and water ecological land, with positive ecological efficiency continuously improving, representing a focus for desertification control and saline-alkali land reuse. The main negative impact transformation types (66.92%) were industrial and agricultural production land occupying grassland ecological land and living land converting to agro-pastoral land. Although Baotou continuously restored conversion land types with negative effects to improve ecological environment quality, the ecological negative effects from converting ecological land to industrial production land in the later period remained unresolved, requiring targeted ecological restoration strategies for these two area types while consolidating positive effect achievements.

4 Discussion

This study analyzed spatio-temporal evolution characteristics of land use transformation in agro-pastoral transitional zone cities using three-phase land use data and land transfer matrices, introducing ecological environment quality index and ecological contribution rate models to analyze ecological quality and effects. The research found that Baotou's land use conversion rate was relatively large, with production land showing a decreasing trend and ecological land dominated by grassland as the main decreasing type, while living land proportion increased rapidly. Agricultural production and grassland ecological land had the largest conversion areas, showing significant "agro-pastoral composite and exchange" characteristics, with enhanced urbanization and settlement of farmers and herdsmen. Land use transformation patterns showed contradictions between economic development and habitat protection due to topographic constraints and urban leading industries and policy orientation, creating obvious differences in habitat quality across urban zones.

Before 2010, land use changes were mainly driven by national key industrial

project demands, enabling rapid urban development. In recent years, under the background of transforming old growth drivers toward sustainable development paths, urban and rural areas have faced varying degrees of population loss and aging, leading to transformed land use patterns. During this process, some grassland towns developed tourism, converting grassland pastoral production functions to ecological functions, resulting in significant changes in suburban and village ecological-production-living spatial patterns.

Overall, we recommend continuing ecological civilization-oriented planning, rationally allocating ecological-production-living spaces according to actual population growth and migration, and coordinating master plans, land use plans, and socio-economic plans. Attention should be paid to Baotou's ecological effects within the "Hohhot-Baotou-Ordos-Ulanqab" urban agglomeration and Yellow River Basin. First, at the production space level, ecological compensation mechanisms should stimulate conversion from agricultural production land to grassland ecological land, while adhering to industrial and mining ecological restoration systems—especially for numerous small-scale mining lands with difficult management implementation—and guiding industries to reduce environmental pollution through technology to improve land ecological security and green production models. Second, at the ecological space level, grassland ecological governance in pastoral banners/counties like Damao Banner should be prioritized, strengthening windbreak and sand fixation functions and water and soil conservation along the southern Yellow River. Restoration area targets for grassland and forest should be established with strengthened post-management, serving as primary land types to balance urban development's negative ecological effects. Optimization schemes for other ecological land should be explored to slow land desertification and salinization, while tapping tertiary industry potential to convert land functions to tourism or other services, enhancing ecological-production-living space coupling. Strict prohibition and rotational grazing systems for grassland should be enforced to prevent human destruction of forest, grassland, water, and wetland resources. Third, at the living space level, ecological effects should be enhanced by promoting high-quality urban development, conducting stock conversion of inefficient industrial land and idle homesteads for reclamation planning and land consolidation, and ensuring growth quality of agricultural and pastoral residents' living land to guarantee sustainable ecological and socio-economic environment development, scientifically coordinating production and living land development between agricultural and pastoral villages. This will promote rational layout of ecological-production-living land in agro-pastoral transitional zone cities, optimize national territorial space allocation, and implement ecological protection and high-quality development.

Study improvement directions include: (1) Research indicators for land use transformation effects on ecological environment quality relate not only to conversion area but could also incorporate ecological factors like climate, soil changes, and species migration. (2) When classifying multifunctional land types, land extraction schemes should be refined according to study area characteristics to analyze dominant functions under various land use patterns.

(3) Ecological environment quality index thresholds and weight definitions involve subjective factors that could be improved by combining study area characteristics. (4) Based on socio-economic development, research should examine driving mechanisms of land use transformation at different stages, deeply analyze internal factors influencing land use changes, and further propose ecological environment protection strategies.

5 Conclusions

(1) Baotou's ecological-production-living spaces showed decreasing production and ecological land and increasing living land, presenting a pattern of "northern pastoralism and southern agriculture," central agro-pastoral interlacing, globally scattered industrial and mining land, a Daqing Mountain ecological protection belt crossing south of the city, and dynamic mountain-hugging expansion of urban land. Among secondary categories, agricultural production land and grassland ecological land had the largest exchange area, while industrial production land and urban living land were the main increasing types.

(2) Baotou's ecological environment quality index declined from 0.629 to 0.619, contrary to major national economic indicators, but the ecological deterioration trend slowed. High-quality ecological zones accounted for the largest proportion (69.45%), mainly distributed in the southern plateau and central-southern Daqing Mountain ecological belt. Medium-high quality zone area decreased stably. Medium-quality zones were distributed in agro-pastoral areas north of Daqing Mountain and agricultural development zones north of the Yellow River. Low-quality zones, related to mining development, continuously decreased in proportion. Low-quality zones as urban socio-economic development areas continuously expanded southeastward.

(3) In ecological-production-living space transformation, grassland ecological land change had the greatest impact on habitat quality. Positive ecological environment effects mainly originated from conversion of other ecological land and agricultural production land to grassland and forest ecological land, while negative effects mainly stemmed from grassland ecological land consumption. Restoration measures for negative effects caused by increasing industrial production and urban living land have achieved remarkable results.

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