Postprint: Spatiotemporal Evolution of Habitat Quality and Scenario Simulation in the Agro-Pastoral Ecotone of Northern China

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Abstract

Investigating the change process and future scenario patterns of habitat quality in vulnerable areas is of great significance for the scientific protection of the ecological environment in the study area. This study, based on land use data, the FLUS-InVEST model, and spatial autocorrelation methods, analyzes the spatiotemporal patterns of habitat quality in the agro-pastoral ecotone of northern China from 2000 to 2020, and conducts multi-scenario simulations of habitat quality for 2040. The results show that: (1) Grassland is the dominant land type in the study area, accounting for more than 41%. From 2000 to 2020, cropland experienced the most significant change, with an area reduction of 10,157 km^2, while forest land and construction land areas increased. (2) The southeastern boundary of the study area exhibits relatively high habitat quality; from 2000 to 2020, the average habitat quality did not change substantially, but the areas of lower-grade and higher-grade habitat quality increased by 2,281 km^2 and 1,375 km^2, respectively, while areas with higher degradation degrees displayed point-like concentrated distribution on some construction lands. (3) Under various scenarios for 2040, habitat quality demonstrates a positive trend, but the improvement is most pronounced under the ecological protection scenario, with the higher-grade area increasing by 2,514 km^2 compared to 2020. It is recommended that future land use planning and ecological environment protection processes should prioritize areas with low habitat quality, such as southeastern Inner Mongolia and northern Hebei.

Full Text

Preamble

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Spatiotemporal Evolution and Scenario Simulation of Habitat Quality in the Agro-Pastoral Ecotone of Northern China

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Abstract

Investigating the change process and future scenario patterns of habitat quality in vulnerable regions is crucial for the scientific protection of ecological environments. This study analyzes the spatiotemporal patterns of habitat quality in the agro-pastoral ecotone of northern China from 2000 to 2020 and conducts multi-scenario simulations for 2040 using land-use data, the InVEST model, and spatial autocorrelation methods. The results indicate that: (1) Grassland is the dominant land-use type in the study area, accounting for over 41% of the total area, followed by cultivated land (>32%) and forest land (>16%). Between 2000 and 2020, cultivated land experienced the most significant change, with an area reduction of 10,157 km^2, while unused land showed the smallest change, decreasing by only 771 km^2. The areas of forest land and construction land increased during this period. (2) Habitat quality is relatively high along the southeastern boundary of the study area. From 2000 to 2020, the average habitat quality index changed from 0.498 to 0.494, indicating little overall change. However, the areas of low-grade and high-grade habitat quality increased by 2,281 km^2 and 1,375 km^2, respectively. Areas with high degradation degrees exhibited point-like concentrations, primarily distributed across certain construction lands. (3) Under all 2040 scenarios, habitat quality shows an improving trend, with the most significant improvement occurring under the ecological protection scenario, where high-grade habitat area increases by 2,514 km^2 compared to 2020. In the trend development scenario, low-grade habitat quality areas decrease by up to 162,625 km^2 relative to 2020. We recommend that future land-use planning and ecological protection efforts prioritize areas with low habitat quality in southeastern Inner Mongolia and northern Hebei.

Keywords: habitat quality; agro-pastoral ecotone of northern China; land use; spatiotemporal pattern

Introduction

The agro-pastoral ecotone of northern China represents a transitional zone between agricultural and pastoral regions and serves as a critical ecological barrier [**?**, **?**]. However, excessive exploitation of natural resources in this region has led to severe ecological problems, including soil erosion, grassland degradation, and land desertification, posing significant challenges to sustainable development [?]. While ecological construction projects such as the "Grain for Green Program" and "National Key Desertification Prevention and Control Projects" have improved the ecological environment, the sustainability of these ecosystems remains uncertain under complex natural conditions and future policy impacts [?].

Habitat quality, which measures the health of ecosystems and serves as an important indicator for coordinating regional development, has been assessed primarily through field surveys and model simulations [?]. Field surveys provide first-hand data and accurate local information but cannot monitor habitat quality dynamics over long time series and are limited by small spatial coverage and high resource demands. Model-based approaches include the Habitat Suitability Index model, MaxEnt model, and InVEST model [?, ?, ?]. MaxEnt requires large samples and high-precision data with complex preprocessing of ecological processes, limiting its applicability. In contrast, the InVEST model, which uses land use as its primary input, offers significant advantages in dynamism, spatialization, multi-level analysis, and modular functionality. Its Habitat Quality module can conveniently and rapidly assess the impacts of different threat factors and land-use/cover changes on ecological quality, making it one of the most widely applied models [?, ?, ?]. Previous studies have coupled land-use models with InVEST to simulate habitat quality scenarios, commonly employing models such as Markov, Logistic, and FLUS that can identify key factors driving land expansion and landscape changes [?, ?, ?].

Current research on habitat quality in the agro-pastoral ecotone has focused primarily on land use, vegetation change, and climate factors. These studies have revealed that cultivated land showed the largest fluctuation, construction land experienced the most dramatic changes, and overall habitat quality was generally favorable, with high-grade habitat quality areas occupying nearly half of the region [?, ?]. However, scenario simulation studies predicting future habitat quality across the entire agro-pastoral ecotone remain scarce. Therefore, this study investigates the spatiotemporal evolution of habitat quality from 2000 to 2020 and couples the FLUS-InVEST models to reveal habitat quality changes under future trend development, ecological protection, economic development, and cultivated land protection scenarios, aiming to provide scientific support for ecological conservation and high-quality development in the agro-pastoral ecotone of northern China.

1.1 Study Area

Various criteria exist for delineating the agro-pastoral ecotone of northern China. This study adopts the boundary defined by Shi et al. [?] based on actual land-use patterns. The study area spans parts of Shanxi, Shaanxi, Gansu, Ningxia Hui Autonomous Region, Hebei, Inner Mongolia, Liaoning, Jilin, and Heilongjiang provinces, forming a belt-shaped region that is wider in the east and narrower in the west, located in southeastern Inner Mongolia [Figure 1: see original paper]. The topography is dominated by plateaus and hills, with some plains and mountains. Elevations range from 29 to 3,664 m, increasing from east to west. Precipitation decreases from south to north, averaging 300–450 mm annually. Temperature decreases from southwest to northeast, with mean annual temperatures of 2–8°C and distinct seasonal variations. The region experiences approximately 30–100 windy days per year and has low vegetation coverage. Soils are primarily loess, chestnut, and brown soils. Due to combined effects of climate, topography, and soil conditions, vegetation consists mainly of cultivated crops and grasslands with interspersed spatial distribution, accompanied by scattered shrubs and broadleaf forests. Long-term over-cultivation, overgrazing, and improper water resource utilization have caused severe ecological degradation.

1.2 Data Sources

Data sources include land-use/cover, vegetation, topography, and other relevant datasets. Land-use/cover data (1980–2020) were obtained from the Resource and Environment Science and Data Center of the Chinese Academy of Sciences at 30 m resolution [?] and resampled to 100 m. MOD13A3 NDVI data were sourced from NASA Earthdata at 1 km resolution. Population grid datasets from WorldPop provided population density data. Annual precipitation and temperature data were obtained from the National Earth System Science Data Center. Digital Elevation Model (DEM) data were acquired from the Geospatial Data Cloud, from which elevation, relief amplitude, and slope were derived. All raster data were unified to a 100 m resolution.

1.3 Methods

1.3.1 Land-Use/Cover Change Analysis Land-use conversion analysis during specific periods is typically based on land-use transfer matrices, which reveal conversion trends, sources, and quantitative characteristics. The expression is [?]:

$$S_{ij} = \begin{bmatrix} S_{11} & S_{12} & \cdots & S_{1n} \\ S_{21} & S_{22} & \cdots & S_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ S_{n1} & S_{n2} & \cdots & S_{nn} \end{bmatrix}$$

where n represents the total number of land-use types; i and j denote initial and final land-use patterns ($i, j = 1, 2, \dots, n$); and S_{ij} represents the area converted from land-use type i to type j during the study period.

1.3.2 Habitat Quality Assessment and Evolution We used the InVEST 3.12 Habitat Quality module to evaluate habitat quality. This method uses land-use/cover data to calculate habitat quality based on threat impacts, distances, habitat suitability, and threat sensitivity [?]. The formulas are:

$$Q_{xj} = H_j \left(1 - \frac{D_{xj}^z}{D_{xj}^z + k^z}\right)$$

$$D_{xj} = \sum_{r=1}^{R} \sum_{y=1}^{Y_r} \left(\frac{w_r}{\sum_{r=1}^{R} w_r}\right) r_y i_{rxy} \beta_x S_{jr}$$

where Q_{xj} is habitat quality; D_{xj} is habitat degradation; H_j is habitat suitability; k is the half-saturation constant; R is the total number of threat factors; Y_r is the number of grid cells with threat factor r; w_r is the weight of threat factor r; r_y is the threat factor value in grid cell y; i_{rxy} is the impact range of threat factor r; β_x is the accessibility level in grid cell x; and S_{jr} is the sensitivity of land-use type j to threat factor r.

Threat factors include cultivated land, urban/rural residential land, and unused land (sand, saline-alkali land, bare rock, bare land, Gobi). Habitat types include forest, grassland, and water ecosystems. Parameters were developed based on existing literature [?], study area characteristics, and expert knowledge [TABLE:1, TABLE:2]. Habitat quality was classified into five levels using natural breaks: low (0–0.46], relatively low (0.46–0.61], medium (0.61–0.80], relatively high (0.80–0.90], and high (0.90–1]. Habitat degradation was similarly classified into five levels.

Spatial autocorrelation was used to analyze the spatial clustering of habitat quality. Global Moran' s I index was calculated as [?]:

$$I = \frac{n \sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij}(x_i - \bar{x})(x_j - \bar{x})}{\sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij} \sum_{i=1}^{n} (x_i - \bar{x})^2}$$

where n is the number of spatial grid cells; x_i and x_j are observed values in units i and j; $\bar{x}$ is the mean value; and w_{ij} is the spatial weight matrix. Moran' s I > 0 indicates positive spatial correlation.

1.3.3 Habitat Quality Scenario Simulation We used the FLUS-InVEST model to simulate 2040 scenarios. The FLUS model consists of an occurrence probability calculation module and a cellular automata (CA) module [?, ?]. The ANN-based probability module generates suitability probabilities, while the CA module incorporates neighborhood effects and conversion costs. The model uses a roulette selection method to determine land-use transitions. Different scenarios require different land-use demands, which were predicted using a Markov chain. Four scenarios were developed: trend development, economic development, ecological protection, and cultivated land protection . Kappa coefficients above 78.9% validated the model accuracy.

Results

2.1 Land-Use/Cover Change Process

Grassland is the dominant land-use type in the agro-pastoral ecotone, followed by cultivated land, with water bodies having the smallest area [Figure 2: see original paper]. Between 2000 and 2020, forest land and construction land areas increased, while other land types decreased. The conversion among cultivated land, forest land, and grassland was most intense, with the largest conversion occurring between cultivated land and grassland. Forest land expansion primarily originated from cultivated land .

2.2 Habitat Quality Assessment and Evolution

Habitat quality in the agro-pastoral ecotone shows distinct spatial variation, dominated by medium and relatively low quality [Figure 3: see original paper]. Medium habitat quality accounts for 50.2% of the area, while relatively low quality comprises approximately 33.6%. Habitat quality is higher in the southeast and lower in the northeast. Temporally, average habitat quality indices were 0.498 in 2000 and 0.494 in 2020, showing a slight decline. High-quality habitat area increased by 1,375 km^2, while low-quality habitat expanded by 2,281 km^2. Areas with medium and above-medium habitat quality decreased by 9,615 km^2.

Habitat degradation is primarily characterized by slight, relatively weak, and moderate degradation, though some areas show strong degradation. Spatially, degradation is relatively low in forest and grassland areas in the southeast, while highly degraded areas appear as point distributions concentrated in construction lands. Temporally, average degradation indices increased from 0.083 in 2000 to 0.091 in 2020, indicating a gradual intensification of degradation.

Global Moran' s I values for habitat quality were 0.654 in 2000 and 0.652 in 2020, indicating significant spatial clustering. Hotspot analysis reveals that hotspots are concentrated in the southeast and northwest where vegetation coverage is high, while coldspots are located in the north and southwest dominated by construction land and cultivated land [Figure 4: see original paper].

2.3 Habitat Quality Scenario Patterns for 2040

Under all 2040 scenarios, land use remains dominated by cultivated land, grassland, and forest land, with water bodies maintaining the smallest area . In the ecological protection scenario, forest land area increases substantially while unused land decreases significantly (2,368 km^2 reduction in unused land, 18,547 km^2 increase in forest land). In the cultivated land protection scenario, existing farmland is protected, resulting in a 2,163 km^2 expansion of cultivated land and a 15,560 km^2 reduction in forest land. Under economic development, forest land decreases by 17,747 km^2 while grassland increases by 12,026 km^2. The trend development scenario shows the most significant grassland expansion and substantial forest land reduction.

Habitat quality under all scenarios is dominated by medium, relatively low, and high grades . High habitat quality is primarily distributed in the southeast. In the 2040 trend development scenario, low-quality habitat areas decrease by 162,625 km^2, while medium-quality areas increase by 147,722 km^2. In the ecological protection scenario, low-quality habitat area decreases by 160,347 km^2 and high-quality area increases by 178,294 km^2. The economic development scenario shows similar patterns to the cultivated land protection scenario.

Overall, habitat quality in the agro-pastoral ecotone shows a deteriorating trend, with ecological problems being relatively severe. The ecological protection scenario demonstrates the most significant improvement in habitat quality [Figure 5: see original paper].

Discussion

The substantial conversion of cultivated land to grassland (16,922 km^2) and the 7,897 km^2 increase in forest land between 2000 and 2020 are closely related to China' s Grain for Green Policy [?]. Water bodies and construction land occupy the smallest proportions among all land-use types. Construction land area continues to grow, likely due to accelerated urbanization, despite policies such as farmland requisition-compensation balance [?]. Under the ecological protection scenario, forest land increases substantially, particularly in Inner Mongolia and Hebei, which may be related to these areas being suitable distribution zones for shrub species such as *Berberis poiretii*, *Sabina vulgaris*, and *Salix cheilophila* [?]. Appropriate aerial seeding of shrub forests could facilitate restoration of degraded lands.

The spatiotemporal patterns of habitat quality are primarily influenced by natural factors including temperature, precipitation, soil, topography, and vegetation coverage. Temperature and precipitation affect ecosystem water supply and biodiversity, while soil type directly influences plant growth and ecosystem productivity. Topographic factors such as elevation and relief affect habitat quality through temperature, water sources, and soil conditions [?]. Areas with high vegetation coverage exhibit higher habitat quality [?], as vegetation growth directly affects ecosystem structure and function. Threat factors such as farmland reclamation, residential construction, mining development, and resource exploitation alter suitable habitats and degrade habitat quality.

Areas with high habitat degradation are concentrated at the interface between forest land and other land types, particularly construction lands [Figure 6: see original paper]. These represent zones of gradually deteriorating ecological quality that require strengthened protection. When construction land and cultivated land proportions are high, ecological environmental quality tends to be poorer, indicating that human activity is another major cause of habitat degradation [?, ?]. Future development should emphasize rational distribution of forest and construction land areas, establish nature reserves, intensify conservation efforts, and promote balanced development of agriculture, forestry, and animal husbandry. Ecosystem protection should reduce unnecessary logging and pruning, implement timely thinning, and adopt ecological restoration and tree species optimization measures. However, the InVEST model involves some subjective factors in determining threat factors, and future research should consider coupling experimental and modeling approaches to minimize errors and provide more comprehensive analysis.

Conclusion

This study reveals significant land-use transitions in the agro-pastoral ecotone of northern China between 2000 and 2020, with cultivated land showing the most dramatic change (10,157 km^2 decrease) and construction land increasing by 8,095 km^2. Spatially, habitat quality is relatively good in the central-east but poor in the southeast. The average habitat quality index decreased slightly from 0.498 to 0.494, while areas of high and low habitat quality increased. Projections for 2040 indicate that high-quality habitat area will increase while low-quality area will decrease, with medium-quality habitat area expanding significantly. The ecological protection scenario shows the most pronounced improvement in high-quality habitat area, which largely coincides with forest land distribution. These findings provide a scientific basis for ecological protection and sustainable development in the agro-pastoral ecotone of northern China.

References

[1] Zhao Halin, Zhou Ruilian, Zhang Tonghui, et al. Grassland vegetation types characteristics and ecological problems in the agriculture pastoral ecotone in northern China[J]. Grassland in China, 2003, 25(3): 2-9.

[2] Su Zhizhu, Ma Yijuan, Liu Mei. Study on the formation of transitional belt between agriculture and animal husbandry in northern China[J]. Journal of Shanxi University (Natural Science Edition), 2003, 26(3): 269-273.

[3] Cui Xiao, Wang Yongsheng, Shi Linna. Spatio temporal characteristics and obstacle factors of human land system coupling coordination in farming pastoral ecotone of northern China[J]. Journal of Agricultural Resources and Environment, 2023, 40(1): 206-217.

[4] Wang Zhiqiang, Chen Zhichao, Hao Chengyuan. Breeding habitat suitability evaluation of Red crown Crane in Zhalong National Nature Reserve by the Method of Habitat Suitability Index[J]. Wetland Science, 2009, 7(3): 197-201.

[5] Bai Xiaojuan, Chen Hai, Liu Di, et al. Spatial differentiation of ecosystem services demand and its bundles based on MaxEnt model: A case study of Mizhi County, Shaanxi Province, China[J]. Acta Ecologica Sinica, 2023, 43(7): 2745-2755.

[6] Xie Yifan, Yao Shunbo, Deng Yuanjie, et al. Impact of the Grain for Green project on the spatial and temporal pattern of habitat quality in Yan’ an City,

China[J]. Chinese Journal of Eco-Agriculture, 2020, 28(4): 575-586.

[7] Zheng Yaping, Zhang Junhua, Tian Huiwen, et al. Spatio temporal characteristics of habitat quality and natural human driven mechanism in Dabie Mountain Area[J]. Environmental Science, 2024, 45(4): 2268-2279.

[8] Wang Peng, Qin Sitong, Hu Huirong. Spatial temporal evolution characteristics of land use change and habitat quality in the Lhasa River Basin over the past three decades[J]. Arid Zone Research, 2023, 40(3): 492-503.

[9] Ren Han, Zhang Jingjing, Zhu Wenbo, et al. Impact of land use change on habitat in the Qihe River Basin of Taihang Mountains[J]. Advances in Geography Science, 2018, 37(12): 1693-1704.

[10] Su Yingqing, Liu Geng, Zhao Jingbo, et al. Multi-scenario simulation prediction of ecological space in the Fenhe River Basin using the FLUS model[J]. Arid Zone Research, 2021, 38(4): 1152-1161.

[11] Ray T C, Dickson G B, Sisk D T, et al. Spatial application of a predictive wildlife occurrence model to assess alternative forest management scenarios in northern Arizona[J]. Forest Ecology and Management, 2014, 322(39): 117-126.

[12] Wu Jiansheng, Cao Qiwen, Shi Shuqin, et al. Spatio-temporal variability of habitat quality in Beijing-Tianjin-Hebei Area based on land use change[J]. Chinese Journal of Applied Ecology, 2015, 26(11): 3457-3466.

[13] Dai L, Li S, Lewis B J, et al. The influence of land use change on the spatial-temporal variability of habitat quality between 1990 and 2010 in Northeast China[J]. Journal of Forestry Research, 2019, 30(6): 2227-2236.

[14] Rong Yuejing, Zhang Hui, Wang Yansong. Assessment on land use and biodiversity in Nanjing based on Logistic-Markov and InVEST Model[J]. Research of Soil and Water Conservation, 2016, 23(3): 82-89.

[15] Liu Mengzhu, Zhang Hongjuan, Ren Heyu, et al. Spatio-temporal variations of the soil conservation function in the Agro-pastoral Ecotone of northern China Under grain for green program[J]. Research of Soil and Water Conservation, 2021, 28(5): 172-178.

[16] Qiu Jiaqi, Yu Deyong. Spatial patterns and influence factors of ecosystem services in the agro-pastoral ecotone of northern China: Taking the central and western regions of the Inner Mongolia as an example[J]. Acta Ecologica Sinica, 2023, 43(18): 7598-7609.

[17] Bai Shuting. Spatio-temporal Changes, Trade-offs and Synergies of Ecosystem Services in Farming-Pastoral Ecotone of Northern China[D]. Beijing: University of Chinese Academy of Science, 2023.

[18] Shi Xiaoli, Shi Wenjiao. Review on boundary shift of farming-pastoral ecotone in northern China and its driving forces[J]. Transactions of the Chinese Society of Agricultural Engineering, 2018, 34(20): 1-11.

[19] Xu Xinliang, Liu Jiyuan, Zhang Shuwen, et al. China multi-period land use land cover remote sensing monitoring data set (CNLUCC)[DB/OL]. Resource and Environment Data Cloud Platform, 2018.

[20] Sharp R, Douglass J, et al. InVEST 3.8.9. User' s Guide[M]. The Natural Capital Project, Stanford University, 2020.

[21] Wang Qikun, Wu Wei, Yang Xueqi, et al. Spatial-temporal changes and driving factors of habitat quality in Shanxi Province during the past 20 years[J]. Arid Zone Research, 2022, 39(5): 1684-1694.

[22] Zhang Xiaodong, Wu Dan, Wang Ying, et al. Spatiotemporal evolution characteristics and influencing factors of habitat quality in Yinchuan City by coupling InVEST and Geodetector models[J]. Arid Land Geography, 2024, 47(7): 1242-1251.

[23] Terrado M, Sabater S, Chaplin Kramer B, et al. Model development for the assessment of terrestrial and aquatic habitat quality in conservation planning[J]. Science of The Total Environment, 2016, 540(47): 63-70.

[24] Fang L, Liu Y, Li C, et al. Spatiotemporal characteristics and future scenario simulation of the trade-offs and synergies of mountain ecosystem services: A case study of the Dabie Mountains Area, China[J]. Chinese Geographical Science, 2023, 33(1): 144-158.

[25] Zhang Xiaolong, Zhou Jihua, Liu Yanxu, et al. Impacts of climate change and human activities on the distribution of shrubbery in Inner Mongolia[J]. Acta Ecologica Sinica, 2020, 40(10): 3237-3248.

[26] Su Dejun, Zhao Xiaojiong, Li Guoxia, et al. Spatial and temporal characteristics and driving factors of habitat quality in Qilian Mountain National Nature Reserve[J]. China Environmental Science, 2024, 44(5): 2595-2605.

[27] Wang J F, Li X H, Christakos G, et al. Geographical detectors-based health risk assessment and its application in the neural tube defects study of the Heshun Region, China[J]. International Journal of Geographical Information Science, 2010, 24(1): 107-127.

[28] Ao Yong, Jiang Lingfeng, Bai Zhaodi, et al. Comprehensive evaluation of land ecological quality in the Yellow River Basin based on Grid GIS[J]. Arid Land Geography, 2022, 45(1): 164-175.

[29] Liu X P, Liang X, Li X, et al. A future land use simulation model (FLUS) for simulating multiple land use scenarios by coupling human and natural effects[J]. Landscape and Urban Planning, 2017, 168(32): 94-116.

[30] Qi B, Yu M, Li Y. Multi-scenario prediction of land use changes and ecosystem service values in the Lhasa River Basin based on Markov Model[J]. Land, 2024, 13(5): 597-621.

[31] Shi Zhigang. Analysis of soil and water conservation in Dabie Mountains[J]. China Water Resources, 2012, 62(12): 31-32.