Spatiotemporal Evolution and Prediction of Habitat Quality in the Bosten Lake Basin Based on the Three Living Spaces: Postprint

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Abstract

Habitat quality is a crucial indicator for assessing the status of regional ecological environments, and investigating habitat quality in arid and semi-arid basin regions holds significant theoretical and practical importance. Based on multi-source data including physical geography and remote sensing imagery, and employing research methodologies such as gravity center migration analysis and the InVEST model, this study reveals the spatiotemporal evolution patterns of habitat quality in the Bosten Lake Basin from 1980 to 2020. The FLUS model is utilized to simulate land use spatiotemporal evolution for 2025 and 2030, thereby elucidating the spatiotemporal evolution patterns of habitat quality under various land use change scenarios. The results demonstrate that: (1) During 1980–2020, the average habitat quality in the Bosten Lake Basin decreased from 0.546 to 0.521. The area of high-quality regions experienced substantial reduction, with the regional centroid shifting northward; concurrently, the area of low-quality habitat regions increased, with the centroid migrating toward the northeast. The overall habitat degradation intensity across the basin has attenuated. (2) Under the natural development scenario, the area of industrial production land and other ecological land in the basin increased significantly; under the ecological priority development scenario, the trend of water ecological land in the basin reversed from decline to growth, transitioning toward grassland ecological land and other ecological land; under the economic priority development scenario, the boundaries of urban residential land and industrial production land in the Yanqi Basin and oasis plains expanded. These findings can provide a scientific foundation for land use planning and habitat quality improvement in arid and semi-arid basin regions.

Full Text

Abstract

Habitat quality is a crucial indicator for measuring the quality of regional ecological environments, and studying habitat quality in arid and semi-arid watershed areas holds significant theoretical and practical importance. Based on multi-source data including natural geography and remote sensing imagery, this study employs research methods such as center of gravity migration and the InVEST model to reveal the spatiotemporal evolution patterns of habitat quality in the Bosten Lake Basin from 1980 to 2020. The FLUS model is used to simulate land use changes in 2025 and 2030, elucidating habitat quality spatiotemporal evolution patterns under different land use change scenarios. The results show that: (1) From 1980 to 2020, the average habitat quality index in the Bosten Lake Basin decreased from 0.546 to 0.521. High-quality habitat areas experienced substantial reduction, with their regional center of gravity shifting northward, while low-quality habitat areas expanded with their center of gravity moving northeastward. The overall intensity of habitat degradation in the watershed weakened during this period. (2) Under the natural development scenario, industrial production land and other ecological land in the watershed increased significantly. Under the ecological priority scenario, the development trend of water ecological land shifted from decline to growth and expanded toward grassland ecological land and other ecological lands. Under the economic priority scenario, the boundaries of urban living land and industrial production land in the Yanqi Basin and oasis plain expanded. These findings provide a scientific basis for land use planning and habitat quality improvement in arid and semi-arid watershed regions.

Keywords: habitat quality; spatiotemporal evolution; estimate; FLUS-InVEST model; Bosten Lake Basin

Introduction

Land serves multiple functions including ecological, production, and living purposes. Unreasonable land development inevitably leads to land use functional degradation such as soil erosion and land fragmentation, affecting regional ecological environmental quality. Habitat quality refers to the capacity of an ecosystem to continuously provide life-sustaining energy for organisms within a certain spatiotemporal range, expressing ecosystem service levels that are closely related to land use changes within the region.

Domestic and international scholars have primarily approached habitat quality research through two methods: constructing indicator systems and model analysis. The InVEST model, SolVES model, and habitat suitability models are mainstream approaches in habitat quality assessment. Among these, the InVEST model is widely applied due to its spatial flexibility, concise data requirements, and reliable results. Literature review reveals that most habitat quality studies in arid and semi-arid regions focus on administrative units such as provinces, cities, nature reserves, and mountain systems, with limited research on arid and semi-arid watersheds. For instance, Chen et al. studied the habitat quality of the Manas River Basin using the InVEST model, while Han et al. evaluated the impact of land use changes on habitat quality in the Qinghai Lake Basin. Most existing studies focus on past and present changes in regional habitat quality, with relatively few predictive studies on future trends, limited integration of multi-scenario land use simulation with habitat quality research, and scarce analyses from production-living-ecological perspectives.

The Bosten Lake Basin features complex land use types and a fragile ecological environment, where ecological space plays a crucial role in watershed habitat quality. Based on the "production-living-ecological space" perspective and referencing relevant land function classification studies, this study classifies land use types in the Bosten Lake Basin into agricultural production land, industrial production land, urban and rural living land, and forest, grassland, water, and other ecological lands. Taking the spatiotemporal evolution of habitat quality as the main research thread, the study selects 1980–2020 as the research period, employs the FLUS-InVEST model to calculate and analyze spatiotemporal evolution patterns of habitat quality in the Bosten Lake Basin, establishes multi-scenario simulations to analyze future change trends, and proposes countermeasures and suggestions to provide effective references and scientific basis for ecological environmental quality improvement in northwestern arid and semi-arid watershed areas.

1 Study Area Overview

Bosten Lake, located in Bohu County, Bayingolin Mongol Autonomous Prefecture, Xinjiang Uygur Autonomous Region, is China's largest inland freshwater lake. It receives water from the Kaidu River upstream and serves as the source of the Kongque River, acting as a natural regulating reservoir for the Kongque River basin and representing an important water source and ecological conservation area in Xinjiang. Based on geographic data and hydrological river network data for major rivers and lakes including the Kaidu River, Kongque River, and Bosten Lake, this study extracted the Bosten Lake Basin boundary using ArcGIS software and determined the research area scope through comparison with publicly available data. The Bosten Lake Basin is located between 83°16 –87°55 E and 42°11 –43°07 N, covering a watershed area of 59,547 km^2. The area includes all of Bohu County, Yanqi Hui Autonomous Prefecture, and Tiemenguan City, most of Korla City, Hejing County, and Heshuo County, and small portions of Luntai County and Yuli County [Figure 1: see original paper].

2.1 Data Sources and Processing

Land use remote sensing data, population, gross domestic product (GDP), average annual precipitation, and average annual temperature data for the

Bosten Lake Basin from 1980 to 2020 were obtained from the Resource and Environment Science and Data Center of the Chinese Academy of Sciences (https://www.resdc.cn/Default.aspx). Land use data were generated through manual visual interpretation using Landsat TM/ETM remote sensing images as the primary data source. Elevation data were obtained from the Geospatial Data Cloud (http://www.gscloud.cn). Road data were sourced from the Geographic Information Professional Knowledge Service System (http://kmap.ckcest.cn). Additional socioeconomic data were obtained from statistical yearbooks.

2.2.1 Land Use Change Simulation

This study employs the Markov model to simulate land use quantity changes and spatial distribution. The key to the Markov model is obtaining the transition probability matrix, expressed as:

$Pij \times (t + 1) =$
$Pij = Pij \leq 1$
$Pij = 1 = 1, 2, \ldots, n$

where S represents land use state, t represents time period, Pij is the system transition probability matrix, and n is the number of land use types in the study area.

The FLUS model consists of five components: suitability probability, neighborhood factor, adaptive inertia coefficient, conversion cost setting, and comprehensive probability calculation. First, the FLUS model selects elevation, slope, and other land use change driving factors (Table 1) for neural network training and suitability probability calculation to generate suitability probability images for land use change in the Bosten Lake Basin. Second, based on land use status data from 1980 to 2020 and suitability probability data, the study sets land use transition cost matrices and neighborhood factor parameters (Table 2) according to actual conditions in the study area and referencing relevant research by Su et al. The resulting land use change simulation data achieved high Kappa accuracy after validation, demonstrating good simulation performance and model applicability.

2.2.2 Habitat Quality Assessment Based on InVEST Model

This study uses the habitat quality model in InVEST 3.10.0 software to assess habitat quality in the Bosten Lake Basin. The habitat quality assessment includes calculations of habitat quality index and degradation degree, both ranging from [0, 1]. The habitat quality index ranges from [0, 0.9]. After referencing relevant studies and considering actual conditions in the study area, the natural breaks classification method was used to divide habitat quality into five intervals: [0~0.19], (0.19~0.49], (0.49~0.79], (0.79~0.88], and (0.88~0.9], corresponding to low quality, relatively low quality, medium quality, relatively high quality, and high quality. The habitat degradation degree ranges from

[0, 0.141], which was divided into five intervals using the natural breaks classification method: [0~0.012], (0.012~0.035], (0.035~0.066], (0.066~0.099], and (0.099~0.141], corresponding to slight degradation, light degradation, moderate degradation, relatively severe degradation, and severe degradation.

Habitat degradation degree (habitat degradation risk index) reflects the disturbance intensity of threat sources on habitats, with values closer to 1 indicating more severe degradation. Habitat quality represents habitat suitability, with values closer to 1 indicating better quality. Referencing studies by Zhu et al. and Fan et al., as well as the InVEST model user guide, and considering actual conditions in the study area, parameters were set for threat factors, maximum threat distance, weights, suitability, and sensitivity (Tables 3 and 4). By inputting land use data and setting necessary parameters such as threat factors and habitat suitability into the InVEST habitat quality module, the study calculated habitat quality index and degradation degree for the Bosten Lake Basin.

2.2.3 Center of Gravity Migration

To more intuitively and accurately reveal the spatial evolution patterns of habitat quality, this study employs the center of gravity migration model to analyze the migration status of different grades of habitat quality in the Bosten Lake Basin. The calculation formula is:

$$X = \Sigma(Ti \times Xi) / \Sigma Ti$$
$$Y = \Sigma(Ti \times Yi) / \Sigma Ti$$

where X and Y are the longitude and latitude coordinates of the center of gravity for various habitat quality regions, Ti is the area of the ith quality patch, Xi and Yi are the longitude and latitude of the geometric center of the ith patch, and n is the total number of patches for each habitat quality type in that year.

2.2.4 Land Use Change Scenario Settings

Land use spatiotemporal evolution is a complex process influenced by various natural geographic and socioeconomic factors. To analyze future land use spatiotemporal evolution and habitat quality changes in the Bosten Lake Basin, this study establishes three scenarios based on actual regional conditions and referencing Chen et al.: natural development, ecological priority, and economic priority.

Natural Development Scenario: Without any constraints, simulation conditions are set according to the land use transition probability matrix and suitable distribution probability in the Bosten Lake Basin from 1980 to 2020, allowing free conversion among all land use types.

Ecological Priority Development Scenario: Conversion of ecological land to other land uses is restricted, with protection for agricultural, forest, grassland, and water areas. In the land use type conversion matrix, agricultural production land, forest ecological land, grassland ecological land, and water ecological land cannot be converted to urban living land, rural living land, or industrial production land, while other land use types can convert freely. In land demand calculations, transition probabilities from agricultural production land, forest land, grassland, and water ecological land to urban/rural living land and industrial production land are reduced by 50%, while transition probabilities to other ecological lands are increased by 30%.

Economic Priority Development Scenario: Production and living land will be the development focus. In the land use type conversion matrix, agricultural production land cannot be converted to living land, while urban living land, rural living land, and industrial production land cannot be converted to water ecological land, with other land use types converting freely. In land demand calculations, transition probabilities from agricultural production land to forest, grassland, water, and other ecological lands are reduced by 50%, while transition probabilities to urban living land and industrial production land are increased by 30%. Transition probabilities from forest land, grassland, and other ecological lands to urban living land and industrial production land are increased by 20%.

3.1 Spatiotemporal Evolution Analysis of Land Use in the Bosten Lake Basin

From 1980 to 2020, the land use pattern in the Bosten Lake Basin underwent significant changes. Agricultural production land fluctuated and decreased overall, with a reduction of 2,248.19 km^2. Grassland ecological land showed a decreasing trend, with a reduction of 5,125.71 km^2. Water ecological land decreased most significantly, with a reduction of 5,312.61 km^2, of which permanent glaciers and snow cover shrank by 94.45%, converting to bare rock and gravel land and grassland. Water resources hold important ecological significance in arid and semi-arid watershed areas. With rising temperatures in Xinjiang in recent years, water ecological land, particularly glaciers, has shrunk substantially. Industrial production land and urban living land showed continuous increasing trends, with increases of 1,154.17 km^2 and 1,107.41 km^2, respectively. Rural living land changed direction in 2020, shifting from increase to decrease. Among ecological lands, water ecological land decreased most, followed by forest ecological land, while grassland and other ecological lands showed decreasing and increasing trends, respectively, with grassland increasing by 2,586.24 km^2 and other ecological land increasing by 583.07 km^2.

3.2 Multi-Scenario Simulation of Land Use Change

Using the FLUS-Markov model, this study simulated land use changes in the Bosten Lake Basin under natural development, ecological priority, and economic priority scenarios for 2025 and 2030 [Figure 2: see original paper].

Natural Development Scenario: The 2025–2030 trends continue those before 2020. Industrial production land shows the largest increase, followed by other ecological land, which increases by 592.37 km^2 and 299.36 km^2, respectively, compared to 2020. Grassland ecological land continues to decrease, with reductions of 682.96 km^2 and 345.21 km^2 in 2025 and 2030, respectively. Other unused land in the northern watershed expands into grassland ecological land, while permanent glaciers and snow continue to melt, with abundant upstream water flowing into the lake, causing the Bosten Lake water boundary to expand outward. Land use changes in the Yanqi Basin and oasis plain become more frequent and complex.

Ecological Priority Development Scenario: Under this scenario, the Bosten Lake Basin land use pattern shows three characteristics. First, urban living land and industrial production land development are constrained, with increases of only 23.51 km^2 and 13.05 km^2, respectively, in 2030. Second, water ecological land shifts from decrease to increase, expanding by 45.46 km^2 and 119.63 km^2 in 2025 and 2030, respectively, with Bosten Lake and the Kongque River boundary showing expansion trends, encroaching on grassland and other ecological lands. Other ecological land shifts from increase to decrease, with reductions of 214.83 km^2 and 56.77 km^2 in 2025 and 2030, respectively. Third, forest ecological land continues to increase, but with minimal change.

Economic Priority Development Scenario: Under this scenario, human production and living settlement areas in the Bosten Lake Basin expand in 2025–2030. Urban living land and industrial production land increase by 12.12% and 47.78%, respectively, compared to 2020. The reduction trend of agricultural production land is curbed, while grassland ecological land decreases by 688.95 km^2. Water ecological land in the northwestern watershed converts extensively to grassland ecological land and other ecological lands. Other ecological land in the southern desert and Gobi encroaches on forest ecological land, decreasing by 583.07 km^2. Changes in production and living land concentrate in the Yanqi Basin and oasis plain, while ecological land changes mainly occur in the northwestern watershed area.

3.3 Spatiotemporal Evolution of Habitat Quality in the Bosten Lake Basin

Based on the InVEST habitat quality module and parameter settings, this study calculated habitat quality indices and degradation degrees for the Bosten Lake Basin from 1980 to 2020 [FIGURE:3 and FIGURE:4].

Temporal Dimension: Habitat quality in the Bosten Lake Basin deteriorated from 1980 to 2020, with the average habitat quality index decreasing from 0.546 to 0.521. High-quality habitat areas showed the most significant reduction, with their area proportion decreasing by 7.78%. Relatively high-quality habitat areas increased by 5,027.79 km^2, primarily converted from high-quality areas. Low-quality habitat areas increased by 355.92 km^2, mainly transferred from medium-quality areas. Medium-quality and relatively low-quality areas showed minimal changes with an overall decreasing trend. Habitat degradation intensity weakened, with the average degradation degree decreasing by 11.12%. Slight degradation areas increased substantially, light degradation areas remained stable, while moderate and relatively severe degradation areas decreased. Highly degraded areas in the oasis plain shrank significantly.

Spatial Dimension: High-quality habitats are mainly distributed in the Tianshan glaciers in the northern watershed, Bosten Lake in the central region, and along river corridors. Relatively high-quality habitats are primarily found in northern mountain valleys and piedmont plains. Medium-quality and low-quality habitats are distributed in the Yanqi Basin and oasis plain, while relatively low-quality habitats are widely distributed in the deserts, Gobi, bare rock, and gravel lands in the central-southern watershed. Analysis of the spatial center of gravity of watershed habitat quality [Figure 5: see original paper] reveals that from 1980 to 2020, high-quality habitat areas in the Tianshan Mountains decreased substantially, shifting from comprehensive coverage to scattered distribution, with the regional center of gravity moving northward by 21.26 km. The relatively low-quality area center of gravity migrated northwestward by 23.3 km, showing the largest change magnitude. The medium-quality area center of gravity moved northeastward by 10.53 km, with minimal change. The centers of relatively low-quality and low-quality areas migrated northwestward and northeastward by 21.46 km and 7.78 km, respectively.

3.4 Multi-Scenario Prediction of Habitat Quality in the Bosten Lake Basin

Using the FLUS-Markov model to simulate land use changes under three scenarios, this study obtained habitat quality indices and spatial distributions for the Bosten Lake Basin in 2025 and 2030 through the InVEST habitat quality model [Figure 6: see original paper].

Natural Development Scenario: Habitat quality in the Bosten Lake Basin continues the pre-2020 deterioration trend, but with varying area changes across regions. The average habitat quality index in 2030 decreases by 1.12% compared to 2020. High-quality and medium-quality areas decrease by 318.89 km^2 and 406.98 km^2, respectively. Low-quality habitat areas continue to radiate outward from Korla City, increasing by 28.93 km^2 and 56.59 km^2 in 2025 and 2030, respectively. Under this scenario, the average habitat degradation degree in 2030 decreases by 7.78% compared to 2020. Relatively severe and severe degradation areas show a shrinking trend, transforming from strip and block distributions to point distributions. Moderate and light degradation areas shift from patchy to ring-shaped distributions, while slight degradation areas occupy the space previously covered by moderate, relatively severe, and severe degradation areas.

Ecological Priority Development Scenario: Under this scenario, habitat quality in the Bosten Lake Basin improves in 2025–2030, with average habitat quality indices of 0.531 and 0.536, respectively. Habitat degradation risk decreases compared to the natural development scenario. High-quality habitat areas shift from decrease to increase, reaching 24,653.67 km^2 and 24,930.23 km^2 in 2025 and 2030, respectively. Relatively low-quality and low-quality areas shift from increase to decrease. High-quality areas expand toward medium-quality and relatively low-quality areas by 40.28 km^2 and 145.76 km^2, respectively, concentrating in water ecological land areas such as lakes and rivers, though with minimal area change. The reduction trend of medium-quality areas is alleviated.

Economic Priority Development Scenario: Under this scenario, habitat quality in the watershed decreases most significantly. The average habitat quality indices in 2025 and 2030 are 0.518 and 0.514, respectively. Low-quality habitat areas further expand, increasing by 404.76 km^2 in 2030, with changes concentrated near human activity settlements and at boundaries between different quality zones in the Tianshan Mountains. Relatively high-quality habitat areas decrease by 583.01 km^2. Relatively low-quality areas encroach on medium-quality and relatively high-quality areas. Habitat degradation degree increases at boundaries between different quality zones, though with minimal change magnitude.

4.1 Analysis of Spatiotemporal Evolution of Habitat Quality

From 1980 to 2020, the habitat quality index in the Bosten Lake Basin decreased by 4.58%, with the primary causes being continuous reduction of high-quality areas and persistent expansion of low-quality areas. High-quality areas are concentrated in the mountainous grassland regions of the northeastern watershed, gradually shrinking due to the combined effects of human factors such as over-exploitation and natural factors such as climate warming. Analysis of land use transfer matrices calculated from processed remote sensing data reveals that water ecological land area continuously decreased, with permanent glaciers and snow cover shrinking by 94.45% and converting to bare rock, gravel land, and grassland. Water resources hold vital ecological significance in arid and semi-arid watershed areas. With rising temperatures in Xinjiang in recent years, water ecological land, particularly glaciers, has shrunk substantially, significantly impacting habitat quality in high-altitude regions—a finding consistent with Chen et al.'s research in the Manas River Basin.

The expansion of low-quality areas is mainly manifested in the increase of other ecological lands and production/living lands. First, sandy and Gobi lands with low vegetation coverage account for a large proportion of the Bosten Lake Basin and continue to increase in area. Second, with socioeconomic development, secondary and tertiary industries such as petrochemicals, agricultural product processing, and tourism have gradually become economic pillars of the watershed, leading to substantial increases in agricultural, industrial production land, and urban living land, continuously squeezing forest and grassland ecological land space. These are common causes of habitat quality degradation, consistent with findings by Zhao et al. and Zhou et al. Although the government has implemented a series of ecological protection policies, ecological restoration speed is far slower than environmental degradation speed caused by economic development due to inherent natural conditions. Direct and indirect impacts of spatiotemporal changes in production and living land have accelerated habitat quality degradation in the watershed.

4.2 Multi-Scenario Analysis of Land Use and Habitat Quality

Under the natural development scenario, habitat quality in the watershed continues to decline, with more drastic land use changes. Urban living land and industrial production land increase in area and concentrate in Korla City—a major transportation hub and material distribution center in northern and southern Xinjiang where secondary and tertiary industries are well-developed. This finding aligns with Ma et al.'s research results. Under the ecological priority scenario, habitat quality improves and habitat degradation intensity weakens, but excessive restriction of urban living land and industrial production land development may affect economic development levels and residents' income and production/living needs, consistent with Gou et al.'s findings. Additionally, this study finds that under this scenario, ecological environmental quality does not improve rapidly but changes slowly according to original development patterns, indicating that habitat quality improvement lags behind planning implementation.

Under the economic priority scenario, land transformation in the watershed prioritizes urban living land, agricultural production land, and industrial production land, seriously affecting ecology and the environment and potentially leading to severe human-land conflicts and human-nature conflicts—a conclusion consistent with Gao et al.'s research. Based on these findings, adjusting regional land use patterns is an effective means to optimize habitat quality. For production and living lands, measures such as reasonably controlling urban boundary expansion, strictly implementing farmland protection systems, and improving land resource utilization efficiency can improve watershed habitat quality. For ecological lands, given the watershed's characteristics of drought, low rainfall, and high evaporation, selecting cold- and drought-resistant plants to increase vegetation coverage, increasing ecological protection compensation, curbing the reduction trend of forest and grassland lands, and formulating long-term ecological restoration plans can gradually improve watershed habitat quality.

5 Conclusions

This study reveals the following key findings: (1) From 1980 to 2020, habitat quality in the Bosten Lake Basin deteriorated, with high-quality areas substantially decreasing and their center of gravity shifting northward, while low-quality areas increased by 355.92 km^2 with their center of gravity moving northeastward. Watershed habitat degradation shows a ring-shaped spatial distribution pattern, though degradation intensity has weakened. (2) For 2025–2030, under the natural development scenario, production and living lands in the watershed further expand while ecological lands face reduction trends. Under the ecological priority scenario, forest ecological land increases, and water ecological land shifts from reduction to expansion toward grassland ecological land. Under the economic priority scenario, the reduction trend of agricultural production land slows, but ecological land boundaries are forced to contract. (3) Adjusting regional land use patterns is an effective approach to optimize habitat quality in the Bosten Lake Basin.

Future research can further optimize habitat quality assessment results by incorporating specific studies on factors influencing land use and habitat quality and adjusting model parameters considering policy factors.

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