

Dynamic Simulation of Land Use Change and Habitat Quality in the Sanjiangyuan Region Based on the PLUS-InVEST Model (Post-print)

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Abstract

Current biodiversity loss exerts adverse effects on ecosystem services, and investigating the spatiotemporal evolution characteristics of land use and habitat quality in the Sanjiangyuan region holds significant importance for ecological conservation and restoration within the area. This study employs the PLUS model and the habitat quality module of the InVEST model to simulate and predict land use changes under multiple scenarios and estimate habitat quality. The results indicate: (1) During the historical period, the transfer from grassland to unused land covered an area of 9663.53 km², representing the largest proportion of all land transfer types, whereas the transfer from unused land to grassland amounted to merely 3659.27 km², revealing severe grassland degradation to unused land in the Sanjiangyuan region. (2) Multi-scenario predictions for land use and habitat quality in 2030 demonstrate that biodiversity conservation outperforms grassland conservation, which outperforms water resource conservation, which in turn outperforms the natural development scenario. (3) The transfer from unused land to grassland yields the highest contribution rate to habitat quality improvement at 0.7167, followed by the transfer from unused land to water bodies at 0.2603. Advancing biodiversity conservation strategies, addressing grassland-livestock conflicts, strengthening governance of unused land, and reducing grassland-to-unused-land transfer are conducive to mitigating habitat quality degradation.

Full Text

Dynamic Simulation of Land Use Change and Habitat Quality in the Three River Source Region Based on the PLUS-InVEST Models

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Abstract

The ongoing decline in biodiversity adversely affects ecosystem services. Investigating spatiotemporal evolution characteristics of land use and habitat quality in the Three River Source Region is crucial for ecological protection and restoration. This study employs the PLUS model and the InVEST model's habitat quality module to conduct multi-scenario simulations predicting land use changes and estimating habitat quality. The results indicate: (1) During the historical period, 9663.53 km² of grassland converted to unused land, representing the largest conversion proportion, while unused land converted to grassland covered only 3659.27 km², indicating severe grassland degradation to unused land in the Three River Source Region. (2) Multi-scenario predictions for 2030 show that biodiversity conservation performs best, followed by grassland protection, then water resources protection, and finally natural development. (3) Among conversion types, converting unused land to grassland contributes most to habitat quality improvement at 0.7167, followed by converting unused land to water bodies at 0.2603. Implementing biodiversity conservation strategies, resolving grassland-livestock conflicts, intensifying unused land management, and reducing grassland-to-unused land conversion will help mitigate habitat quality decline.

Keywords: Three River Source Region; land use change; habitat quality; InVEST model; PLUS model

Global temperatures continue to rise, with increasing concentrations of greenhouse gases such as carbon dioxide in the atmosphere. Biodiversity loss has become a critical issue. The Millennium Ecosystem Assessment report released in 2005 indicated that over 60% of global ecosystems are degrading, with ecosystem service functions declining annually. Habitat quality reflects an ecosystem's capacity to provide suitable living conditions for species, including material supply and environmental support, and serves as an indicator of biodiversity and ecosystem services. Climate change exacerbates negative impacts on bio-

diversity, particularly under high-emission scenarios, while unreasonable land use changes cause habitat fragmentation, degradation, and loss, recognized as a primary driver of biodiversity decline. The Three River Source Region, as an important freshwater supply area in China, a sensitive zone for climate change in East Asia and globally, and one of the world's most concentrated high-altitude biodiversity hotspots, plays a vital role in maintaining national ecological security and water resource balance. Exploring regional habitat quality spatiotemporal evolution and analyzing land use change impacts on habitat quality are significant for improving regional habitat quality, promoting sustainable development, and protecting biodiversity.

Numerous scholars have studied habitat quality using various methods. International research primarily focuses on four categories: (1) Comprehensive index methods using indices or scoring systems, such as Munné et al.'s index for assessing river riparian habitat ecological quality; (2) Bio-indicator methods monitoring specific biological groups like plants, insects, or birds; (3) Environmental variable monitoring measuring soil, air, and water quality; and (4) Ecological modeling simulating habitat change impacts, such as Mondal et al.'s machine learning model evaluating Sundarbans mangrove habitat quality evolution. Domestic research emphasizes habitat quality estimation methods, land use impacts, spatiotemporal changes, and driving factors. For example, Wang et al. used biotic indices to assess benthic habitat quality in Laizhou Bay, while Liu et al. employed InVEST and GeoDetector to analyze habitat quality patterns and drivers in the Inner Mongolia Yellow River Basin. Future prediction represents a key research direction, with land use prediction models coupled with ecological models being commonly used. With improving remote sensing data resolution and accuracy, more refined data support is available for land use change research, providing reliable foundations for habitat quality studies.

Common habitat quality models include InVEST, IDRISI, MaxEnt, and others. The InVEST (Integrated Valuation of Ecosystem Services and Trade-offs) model offers advantages including operational convenience, minimal parameter requirements, accessible data, precise analysis capabilities, and visualized results. Mainstream land use change models include Markov, CLUE-S, CA-Markov, FLUS, and PLUS. The PLUS (Patch-generating Land Use Simulation Model) model, based on cellular automata, represents an emerging patch-generating land use prediction model with high simulation accuracy and simple operation.

1 Data and Methods

1.1 Study Area

The Three River Source Region is located at 31°39'–36°16'N, 89°24'–102°23'E, covering the core area of the Qinghai-Tibet Plateau in southern Qinghai Province with an area exceeding 30×10^4 km². The terrain slopes from west to east, dominated by plateaus, mountains, and basins, with natural grassland as the primary land use type. As the source of the Yangtze, Yellow,

and Lancang Rivers, the region serves as one of China's most important freshwater supply areas, known as the "Water Tower of China," playing a critical role in maintaining national ecological security and water resource balance. The region is an important ecological function zone and a key global biodiversity conservation area, hosting numerous rare species such as Tibetan antelope, snow leopard, and Himalayan yew, with extremely high ecological value and scientific research significance [Figure 1: see original paper].

1.2 Data Sources and Processing

This study uses five-phase land use data for the Three River Source Region as the foundation, analyzing spatiotemporal evolution characteristics of land use and habitat quality from 2000-2020 and conducting multi-scenario predictions for 2030. Data for simulating future land use include land use data, threat source parameters, and land use type sensitivity parameters. Based on driver factor availability, timeliness, and significance principles, we selected digital elevation model (DEM), population, GDP, and 11 other drivers as PLUS model inputs. All data were unified to 30 m resolution raster format with consistent row and column numbers, geographic coordinate system $GCS_WGS1984$, and projection coordinate system $AsiaNorthAlbersEqualAreaConic$. Meteorological data including precipitation, temperature, and evapotranspiration were processed using inverse distance weighting, while Euclidean distance analysis was applied to distances from settlements, water bodies, and roads.

1.3.1 Multi-scenario Settings

Considering the "Qinghai Sanjiangyuan Ecological Protection and Construction Phase II Project Plan" (2014) and the "Sanjiangyuan National Park Master Plan (2023-2030)" (2023), which propose increasing comprehensive vegetation coverage and maintaining wetland area by 2030, we established four scenarios in the PLUS model: natural development, grassland protection, water resources protection, and biodiversity protection.

(1) Natural Development Scenario. Based on 2000-2020 land use change patterns, maintaining original land transfer probabilities and neighborhood weights.

(2) Grassland Protection Scenario. Construction land conversion was not set. Transfer probabilities were adjusted to reduce grassland-to-cropland/unused land conversions by 50% and increase cropland/unused land-to-grassland conversions by 30%.

(3) Water Resources Protection Scenario. Construction land conversion was not set. Water body-to-forest/grassland/unused land conversions were reduced by 50%, while cropland/unused land-to-water conversions were increased by 30%.

(4) Biodiversity Protection Scenario. Construction land conversion was not set. Forest and grassland-to-cropland conversions were reduced by 50%, cropland-to-forest/grassland/water conversions increased by 30%, and unused land-to-forest/grassland/water conversions increased by 50%.

The PLUS model comprises the Land Expansion Analysis Strategy (LEAS) module and the Cellular Automata (CARS) module based on multi-type random patch seeds. The LEAS module uses random forest algorithms to calculate driver impacts on land use expansion between two periods, obtaining development probabilities:

$$P(d|X) = \frac{1}{M} \sum_{n=1}^M I[h_n(X) = d]$$

where X is the driver factor vector, M is the number of decision trees, d indicates whether conversion is allowed, $h_n(X)$ is the calculated land use type from decision tree n , and I is the indicator function.

The CARS module integrates multi-type random patch seeds and threshold decreasing mechanisms in cellular automata, dynamically simulating patch generation under development probability constraints:

$$OP_{i,k}^t = P_{d,i,k} \times \Omega_{i,k}^t \times D_k^t \times (1 - s_k^t)$$

where $OP_{i,k}^t$ is the overall probability, $P_{d,i,k}$ is the development probability, $\Omega_{i,k}^t$ is the neighborhood effect, D_k^t is the adaptive driving coefficient, and s_k^t represents the constraint on land use type k .

1.3.4 Contribution Rate of Land Use Transitions to Habitat Quality

This study uses habitat quality contribution rate to analyze land use conversion impacts. The formula is adapted from ecological contribution rate:

$$R_{ij} = \frac{(H_j - H_i) \times S_{ij}}{S_t} \times 100\%$$

where R_{ij} is the contribution rate of converting land type i to j , H_i and H_j are initial and final habitat quality indices, S_{ij} is the conversion area, and S_t is the total regional area.

2.2 Land Use Change

2.1 Model Accuracy Verification

Using 2000 and 2010 data, the LEAS module generated development probabilities, and the CARS module simulated 2020 land use. Comparison with actual

2020 data yielded a Kappa coefficient of 0.86, indicating high accuracy and reliable reflection of land use change patterns [Figure 2: see original paper].

2.2.1 Land Use Change 2000-2020

Grassland dominated the Three River Source Region, distributed across most areas except western unused land and western water bodies. Forests were mainly distributed in eastern Xinghai, Tongde, Maqin, and Henan Mongolian Autonomous County, as well as in Jiuzhi, Banma, and southern Yushu City and Nangqian County. Water bodies were found in eastern Maduo County and western Zhiduo County and Golmud's Tanggula Township. Cropland was scarce, mainly in northeastern Xinghai and Tongde counties. Construction land was extremely rare [Figure 3: see original paper].

From 2000-2020, grassland area decreased from 87.98% to 86.03% of the region [Figure 4: see original paper]. The primary conversion was grassland to unused land (9663.53 km²), mainly due to overgrazing. Unused land converted to grassland and water bodies (3659.27 km² and 1162.41 km² respectively), showing ecological restoration potential. Water bodies converted to unused land (923.88 km²), while forest-to-grassland conversion (570.01 km²) was less than grassland-to-forest conversion (779.21 km²), indicating ecological structure optimization. Cropland-to-grassland conversion (44.60 km²) was less than grassland-to-cropland conversion (60.70 km²), likely related to agricultural development needs [Figure 5: see original paper].

2.2.2 Multi-scenario Prediction 2030

PLUS model predictions for 2030 show [FIGURE:6, TABLE:5]:

Natural Development Scenario: Cropland and unused land increase by 29.11% and 12.27% respectively, while forest, grassland, and water bodies decrease by 1.56%, 7.65%, and 1.12%. Vegetation area reduction necessitates protection measures.

Grassland Protection Scenario: Cropland and grassland increase by 1.44% and 6.38%, while forest, water bodies, and unused land decrease by 0.47%, 1.02%, and 8.27%. Forest and grassland areas exceed natural development scenario levels.

Water Resources Protection Scenario: Cropland, water bodies, and unused land increase by 28.82%, 4.07%, and 9.11%, while forest and grassland decrease by 1.56% and 1.16%. Water area exceeds natural development scenario, but forest and grassland protection is insufficient.

Biodiversity Protection Scenario: Cropland, grassland, and water bodies increase by 12.66%, 0.65%, and 3.34%, while forest and unused land decrease by 1.46% and 6.60%. Forest, grassland, and water areas exceed natural development scenario, with most significant unused land management.

2.3 Habitat Quality Change and Land Use Impact

2.3.1 Habitat Quality Change 2000-2020

InVEST Habitat Quality module calculations dividing habitat quality into five grades ([0-0.2], (0.2-0.4], (0.4-0.6], (0.6-0.8], (0.8-1]) show high-habitat-quality areas dominate but fluctuate downward, decreasing from 91.55% to 89.98% [FIGURE:7, FIGURE:8]. The primary reason is high-habitat-quality grassland converting to low-habitat-quality unused land, accounting for 54.32% of total conversion area. Grassland-to-water conversion contributes positively but with insufficient area to significantly increase high-habitat-quality zones. Low-habitat-quality areas increase from 8.12% to 9.74% due to unused land expansion from grassland conversion [Figure 9: see original paper].

2.3.2 Contribution Rate of Land Use Type Transitions to Habitat Quality

Conversions from unused land to cropland, forest, grassland, and water bodies, and from cropland to forest, grassland, and water bodies positively contribute to habitat quality. Conversions from cropland, forest, grassland, and water bodies to unused land negatively impact habitat quality. Unused land-to-grassland conversion shows the highest positive contribution rate (0.7167), followed by unused land-to-water conversion (0.2603). Grassland-to-unused land conversion exhibits the most negative contribution rate (-0.7167), with water-to-unused land conversion also significantly negative (-0.2603) [Figure 10: see original paper].

2.3.3 Multi-scenario Prediction 2030

Predicted 2030 habitat quality indices are: natural development (0.8927), grassland protection (0.9012), water resources protection (0.8965), and biodiversity protection (0.9103) [Figure 11: see original paper]. Biodiversity and grassland protection scenarios significantly improve habitat quality, with biodiversity protection performing best, consistent with land use change predictions.

3 Discussion

Based on the Three River Source Region's ecological characteristics, constructing grassland protection, water resources protection, and biodiversity protection scenarios provides scientific foundations for regional ecological conservation and sustainable development. Grassland-to-unused land conversion is the primary cause of habitat quality decline, while biodiversity protection shows the most significant improvement effect, demonstrating the close connection between land use change and habitat quality.

From the land use perspective, grassland-to-unused land conversion represents the largest area and most significant negative impact, likely related to overgrazing and grassland ecosystem degradation. As the dominant land use type,

grassland' s ecological function degradation directly affects regional ecological balance and biodiversity. Unused land increase reflects grassland ecosystem degradation and indicates ineffective ecological restoration measures. Resolving grassland-livestock conflicts, strengthening grassland management, and intensifying unused land ecological restoration are key to improving regional ecological quality.

From the habitat quality perspective, biodiversity protection scenario yields the highest habitat quality index, most effectively enhancing ecosystem service functions. This emphasizes biodiversity conservation' s importance in ecosystem management and demonstrates that rational land use planning and ecological protection measures can effectively improve regional ecological quality. Under biodiversity protection scenario, increased forest, grassland, and water areas play crucial roles in habitat quality improvement.

Domestic and international scholars generally agree that grassland, forest, and water bodies contribute most to habitat quality, while unused land and cropland contribute less. This study confirms these findings and further quantitatively reveals unused land' s significant restoration potential through conversion to grassland. Although multi-scenario simulations reveal dynamic relationships between land use change and habitat quality, limitations exist. The InVEST habitat quality module lacks specific species data, and threat and sensitivity factors primarily derive from previous studies with insufficient specificity. Socioeconomic factor analysis is limited, not fully considering human activity impacts. Future research should incorporate biodiversity data, optimize threat and sensitivity factors, and strengthen socioeconomic factor analysis to explore human activity-ecosystem service interactions, providing comprehensive theoretical support for regional ecological protection and sustainable development.

4 Conclusions

Based on 2000-2020 land use and habitat quality spatiotemporal analysis with predictions for 2030, main conclusions are:

- (1) From 2000-2020, 9663.53 km² of grassland converted to unused land, while only 3659.27 km² of unused land converted to grassland. Serious grassland-to-unused land degradation is the primary cause of habitat quality decline. Resolving grassland-livestock conflicts, intensifying unused land management, reducing grassland-to-unused land conversion, and continuing forest and water protection are necessary.
- (2) Comparing natural development and biodiversity protection scenarios shows increased forest, grassland, and water areas. Grassland protection scenario increases forest and grassland, while water resources protection scenario only increases water area. Biodiversity protection performs best, followed by grassland protection, then water resources protection, and finally natural development, consistent with land use change predictions.

- (3) Water bodies, forest, and grassland show high habitat quality, cropland shows medium quality, and unused land shows low quality. Unused land-to-grassland conversion contributes most to habitat quality improvement (0.7167), followed by unused land-to-water conversion (0.2603). Grassland-to-unused land conversion has the most negative impact (-0.7167), followed by water-to-unused land conversion (-0.2603). Implementing biodiversity conservation strategies, resolving grassland-livestock conflicts, and strengthening unused land management will mitigate habitat quality decline.

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