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Spatio-Temporal Simulation and Change Analysis of Land Use on the Qinghai-Tibet Plateau Under Future Scenarios

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Abstract

As a sensitive response zone to global change and a critical ecological barrier, the Qinghai-Tibet Plateau's land use and land cover change (LUCC) profoundly impacts regional ecological security and sustainable development. To systematically analyze its evolution patterns and project future trends, this study integrated three phases of remote sensing data from 2000 to 2020. coupled with multi-source drivers including topography, climate, vegetation, and socioeconomic factors. Employing the PLUS (Patch-generating Land Use Simulation) model, we simulated and revealed the spatiotemporal differentiation and transformation mechanisms of LUCC on the Tibetan Plateau over the past two decades. We further projected land use patterns for 2060 under three scenarios: Natural Development (ND), Water Resource Protection (WP), and Sustainable Development (SD). Results indicate: ①Between 2000 and 2020, the land use structure of the Qinghai-Tibet Plateau generally maintained a pattern of "grassland as the dominant type, with unutilized land as the secondary type." Grassland area increased from 132.26×10^4 km^2 to 134.73×10^4 km^2, and its proportion rose from 51.37% to 52.33%. Unutilized land decreased from 101.57×10^4 km^2 to 98.57×10^4 km^2, with its proportion declining from 39.45% to 38.28%; Forest land, water bodies, and constructed land all showed slight increases, while cultivated land decreased marginally. Overall changes were limited in magnitude but exhibited clear trends. ②Significant spatial differentiation in LUCC emerged, revealing a gradient pattern: concentrated forest land in the southeast, extensive grassland in the central region, and dominant unutilized land in the northwest. Constructed land expanded slowly along river valleys and transportation corridors in a "point-axis" pattern. ③Multi-scenario simulations indicate that by 2060, the SD scenario demonstrates the most optimal comprehensive performance in ecological conservation and construction control; the WP scenario significantly promotes the expansion of forest and water areas; while the ND scenario may delay ecological improvement processes. The land use evolution mechanisms clarified under these policy scenarios provide scientific basis for optimizing territorial space and advancing ecological conservation and restoration on the Qinghai-Tibet Plateau.

Keywords

Qinghai-Tibet Plateau; Land use change; PLUS model; Multi-scenario simulation

1. Introduction

As the world's highest and most topographically complex giant landform unit, the Qinghai-Tibet Plateau is hailed as the "Roof of the World" and the "Water Tower of Asia." Its unique geographical patterns and ecological processes occupy an irreplaceable strategic position within global ecosystems[1]. cover change (LUCC) in this region not only directly regulates the stability of the plateau's ecological security barrier function and water conservation capacity, but also profoundly impacts the Asian monsoon system, downstream watershed ecological security, and even the global climate system through processes such as atmospheric circulation, water cycle, and biogeochemical cycles[2] . In recent years, under the dual pressures of global warming and intensified human activities, LUCC processes on the Tibetan Plateau have accelerated. This is primarily manifested in ecological issues such as the degradation of alpine meadows, the retreat of glaciers and permafrost, the weakening of wetland ecosystem functions, and the continuous expansion of urban construction land . These changes are profoundly altering the plateau's landscape patterns and posing a serious threat to regional ecological security[3].

Deeply revealing the spatiotemporal evolution patterns of LUCC on the Qinghai-Tibet Plateau holds significant value for refining the theory of human-land system coupling in alpine regions and advancing mountain ecology and land change science . Accurately predicting its future trajectory and scientifically assessing ecological impacts under different development pathways carry major strategic significance for optimizing the ecological security barrier system on the plateau, reconciling conflicts between ecological conservation and regional development, and safeguarding national ecological securityCurrent research urgently requires establishing a comprehensive framework capable of systematically analyzing the multi-scale driving mechanisms of LUCC and accurately simulating its complex evolution processes, thereby addressing deficiencies in existing theoretical systems and methodological techniques[4] .

This study introduces the PLUS model, which possesses robust spatial simulation and multi-scenario analysis capabilities. By integrating the Land Expansion Analysis Strategy (LEAS) and Cellular Automata with Random Seeded Patches (CARS), this model effectively uncovers the underlying drivers of land use change and precisely simulates spatial evolution at the patch level [5]. Based on three phases of high-resolution land use remote sensing data from 2000 to 2020, combined with multi-source environmental factors and socioeconomic datasets, this study systematically analyzes the spatiotemporal differentiation characteristics and transformation pathways of LUCC on the Tibetan Plateau over the past two decades. Three policy scenarios—natural development, water resource conservation, and sustainable development—were constructedto simulate and predict the plateau's land use patterns by 2060[6]. Ecological impacts under each scenario were assessed through multidimensional evaluation, revealing the response mechanisms of the land use system to global change and regional policies. This provides scientific basis for optimizing the ecological security barrier of the Qinghai-Tibet Plateau[7].

2. Study Area and Methods

2.1. Study Area

The Qinghai-Tibet Plateau, located in the southwestern frontier of China, spans geographical coordinates between 73° 19′ - 104° 47′ E and 26° 00′ - 30° 47′ N. With an average elevation exceeding 4,000 m, it is renowned as the "Roof of the World" and the "Third Pole of the Earth." Its topography exhibits a west-high, east-low gradient, covering a total area exceeding2.5 × 10^6km^2 2, accounting for one-fourth of China's total land area (Figure 1). The plateau exhibits complex and diverse climatic conditions, with annual mean temperatures and precipitation decreasing from southeast to northwest. Influenced by topography and hydrothermal conditions, vegetation types progress from southeast to northwest as follows: forests, shrub steppes, alpine meadows, alpine steppes, and alpine desertsPermafrost is widespread across the plateau, with most areas covered by natural grasslands. As the dominant ecosystem on the plateau, grassland ecosystems concentrate 60% - 80% of the subsurface biomass within the top 0 - 10 cm soil layer[8] .

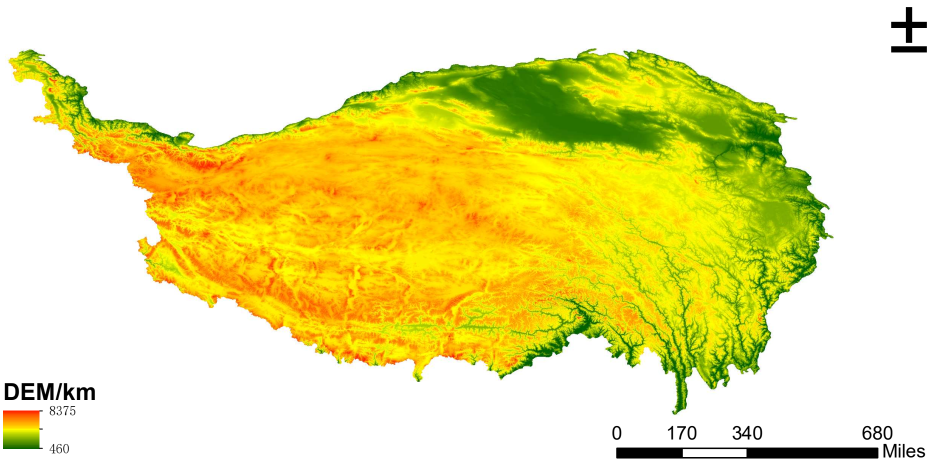

Figure 1. Overview Map of the Study Area

2.2. Data Sources and Processing

2.2.1. Land Use Data

Vegetation type data were obtained from the National Glacier, Permafrost, and Desert Scientific Data Center, with a spatial resolution of 500 meters and covering the years 2000, 2010, and 2020 (Table 1). . Primary vegetation types include coniferous forest, hard-leaved shrub, deciduous shrub, mixed forest, dense shrub, desert shrub, tufted grass, grassland, low-cover grassland, and non-vegetated areas[9] . Table 1 lists 16 influencing factors for vegetation type change and carbon storage change, including topographic factors, climatic factors, other natural factors, and socioeconomic factors. DEM data were sourced from the Geospatial Data Cloud (https://www.gscloud.cn/) with a spatial resolution of 90 meters. Slope gradient and aspect were extracted from the DEM data using ArcGIS 10.8 . For climatic factors, temperature, precipitation, and sunshine duration were obtained through Kriging interpolation using ArcGIS 10.8 based on meteorological station data from the China Meteorological Data Sharing Network . FVC data were extracted from Landsat remote sensing imagery using ENVI 5.3. ArcGIS 10.8's Euclidean distance analysis tool calculated distances to forested areas, rivers, lakes, grasslands, farmlands, towns, and roads.

Table 1. Land Use Data and Driving Factor Sources

Data Type	Name	Year	Source
Land Use Data Driver Factor Data	LUCC NDVI Annual Average Tempera- ture Annual precipitation DEM Slope Distance to river Distance to railway Distance to main road Distance to Secondary Road Distance to city center Population GDP	2000, 2010, 2020 2000, 2010, 2020 2000, 2010, 2020 2000, 2010, 2020 — — 2020 2020 2020 2020 2020 2020 2000, 2010, and 2020	National Glacier, Frozen Soil, and Desert Science Data Center National Qinghai-Tibet Plateau Scientific Data Center National Qinghai-Tibet Plateau Scientific Data Center National Qinghai-Tibet Plateau Scientific Data Center (Geospatial Data Cloud Geospatial Data Cloud OpenStreetMap OpenStreetMap OpenStreetMap OpenStreetMap OpenStreetMap Open Spatial Demographic Data and Research

2.3. Research Methodology—PLUS Model

2.3.1. Multi-Scenario Framework

(1) Natural Development Scenario: Using 2010 and 2020 land use data as baselines, Markov chains were employed to forecast land use demand under natural conditions by 2060 . This scenario assumes future land use changes will follow historical trajectories without significant intervention from specific ecological conservation policies, reflecting an inertial development path under existing economic growth models and population growth trends.

(2) Water Resource Protection Scenario: Building upon the 2010–2020 conversion probabilities, this scenario reduces the probability of water bodies converting to land types other than cropland and forest land by 60%, increases the probability of construction land converting to water bodies and forest land by 10%, a 40% increase in the probability of grassland converting to water bodies and forest land, a 40% and 20% increase in the probability of unutilized land converting to water bodies and forest

land respectively, a 50% decrease in the probability of forest land converting to farmland and grassland, and a 20% increase in the probability of farmland converting to forest land. This scenario aligns with the national strategy for protecting the "Qinghai-Tibet Plateau Ecological Barrier Zone" and the requirements of the "Strictest Water Resource Management System," aiming to maximize the water conservation and ecological barrier functions of the plateau as the "Asian Water Tower." Its core objective is to promote the expansion of ecological land types with significant water conservation functions, such as water bodies and forest land.

(3) Sustainable Development Scenario: Building upon the 2010-2020 conversion probabilities, this scenario reduces the probability of farmland and forestland converting to construction land by 10%, decreases the probability of grassland and water bodies converting to construction land by 20%, and lowers the probability of construction land converting to grassland, water bodies, and unutilized land by 10%. This scenario aligns with the core principles of the United Nations 2030 Sustainable Development Goals (SDGs) and China's "Ecological Civilization Construction," aiming to balance ecological conservation with socioeconomic development. Its objectives include strictly controlling inefficient expansion of construction land, safeguarding basic farmland and critical ecological land, and achieving coordinated regional development.

2.3.2. Domain Weights

$$X^* = \frac{X - X_{min}}{X_{max} - X_{min}}$$

Where X*denotes the standardized deviation value, X represents the change in area across land categories between two periods of land use data; Xmaxis the maximum change in area across all land categories, Xminis the minimum change in area across all land categories .

Based on the above formula, the results for each scenario are calculated by comparing the previously computed land use demand with the data from the preceding year. The weights are then computed. The calculated domain weights are shown in Table 3:

Table 2. Domain Weights

Type	Arable Land	Forest Land	Grassland	Water Areas	Construction Land	Unutilized land
Natural Development	0.52	0.51	0.54	1.00	0.52	0.01
Water Resource Protection	0.54	1.00	0.01	0.89	0.55	0.34
Sustainable Development	0.53	0.52	0.56	1.00	0.51	0.01

2.3.3. Accuracy Validation

The Kappa coefficient is a commonly used method for verifying accuracy, calculated as follows:

$$Kappa = \frac{P_a - P_b}{1 - P_b}$$

Where Parepresents the proportion of correctly simulated rasters; Pbrepresents the proportion of pre-set correctly simulated rasters. 1 indicates the proportion of correctly simulated rasters under ideal conditions. The Kappa coefficient ranges from 0 to 1, with higher values indicating greater simulation accuracy . Simulation accuracy is referenced in Table 4 below:

Table 4. Kappa Coefficient Classification Evaluation Criteria

Kappa Coefficient	<0.00	0.00–0.20	0.21–0.40	0.41–0.60	0.61–0.80	0.81–1.00
Level	Poor	Weak	Weak	Moderate	Significant	Best

Simulating land conditions for 2020, the Kappa coefficient was used to compare the simulation results with the actual 2020 situation, with a sampling rate set at 5%. Through confusion matrix analysis, the Kappa coefficient value was calculated as 0.83 based on the formula, yielding an overall accuracy of 0.90. Comparing with the table, Kappa > 0.8 indicates that the simulation achieved good results with high accuracy.

3. Research Findings

3.1. Spatiotemporal Evolution Characteristics of Land Use in the Qinghai-Tibet Plateau from 2000 to 2020

From 2000 to 2020, the land use structure of the Qinghai-Tibet Plateau largely maintained its fundamental pattern of "grasslands as the dominant land type, followed by deserts, with scattered forest and water conservation projects." Grassland area increased slightly from 132.26×10^4 km² (51.37%) in 2000 to 134.73×10^4 km² (52.33%) in 2020, remaining generally stable. Unutilized land area decreased steadily from 101.57×10^4 km² (39.45%) to 98.57×10^4 km² (38.28%), reflecting positive ecological recovery signals in some regions. Forest land area grew slowly from 19.35×10^4 km² (7.51%) to 19.71×10^4 km² (7.66%), water bodies expanded from 3.20×10^4 km² (1.24%) to 3.46×10^4 km² (1.34%), while construction land marginally increased from 932 km² (0.04%) to 945 km² (0.04%), indicating limited human impact.

Spatial distribution analysis in Figure 2 reveals that grasslands exhibit stability, primarily due to their widespread distribution as the matrix of the plateau ecosystem, especially in contiguous areas of central regions like the Qiangtang Plateau and Kekexili. The reduction in unutilized land (mainly desert) is spatially concentrated in the Ali region of the plateau's northwest and the southern margin of the Qaidam Basin, aligning with the implementation areas of ecological projects such as grazing cessation and grassland restoration, as well as desertification control in certain regions. The gradual expansion of forested land occurs mainly in the Hengduan Mountains of southeastern Tibet and the eastern Qilian Mountains. Constrained by topography and hydrotemperate conditions, its growth is limited in scale but exhibits good sustainability. The spatial expansion of water bodies is closely linked to rising water levels and increased surface areas of inland lake clusters on the plateau (e.g., Selin Co, Zhari Namco), reflecting recent hydrological responses to increased glacial meltwater and precipitation changes. The slight increase in construction land exhibits typical characteristics of "scattered points and roadside distribution," primarily concentrated in towns along major transportation corridors such as the Qinghai-Tibet Highway and Sichuan-Tibet Highway, as well as in the "One River and Two Rivers" region. Its overall proportion remains extremely low, reflecting the slow pace and spatial constraints of urbanization across the Qinghai-Tibet Plateau.

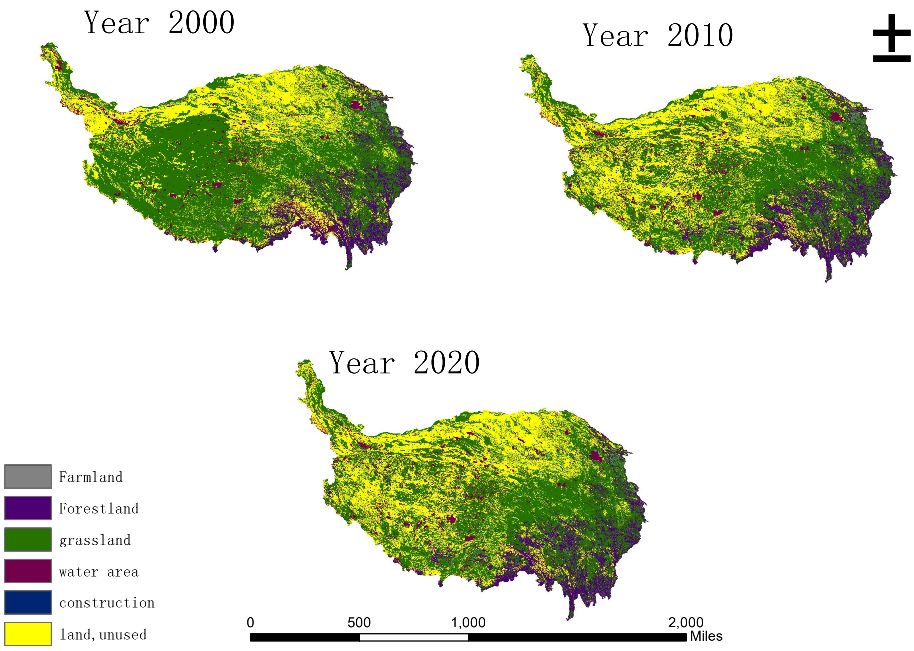

Figure 2. Spatial Distribution of Land Use on the Qinghai-Tibet Plateau, 2000 – 2020

3.2. Spatiotemporal Changes in Land Use by 2060 Under Different Scenarios

Land use patterns across the Qinghai-Tibet Plateau exhibit significant variations under different scenarios from 2020 to 2060. Across three distinct projection scenarios, the areas of construction land, forest land, and water bodies all increase, while grassland and cultivated land areas show a decreasing trend. The expansion of construction land is primarily concentrated in the Yarlung Tsangpo River valley in southern Tibet and the Huangshui River valley in Qinghai. Water body expansion is particularly pronounced in the northern Tibetan Plateau, with significant increases in the areas of many lakes and rivers. Grassland areas in the northern Tibetan Plateau and the Ali region also experience varying degrees of reduction. Cultivated land areas show a marked decline in northeastern Qinghai, southwestern Gansu, and central Tibet.

Simulation results across scenarios revealed significant variations in the magnitude and spatial distribution of land use changes. For arable land, the WP scenario showed the most pronounced reduction, decreasing by 0.055×10^4 km^2 (-6.40%), primarily occurring in northeastern Qinghai, southwestern Gansu, and central Tibet. while under the ND and SD scenarios, changes were smaller at -0.001×10^4 km^2 (-0.19%) and $+0.001\times10^4$ km^2 (+0.11%), respectively. Forest land changes were most pronounced under the WP scenario, increasing by approximately 1.465×10^4 km^2 (+12.77%), primarily distributed in southeastern Tibet and western Sichuan. Under the ND and SD scenarios, forest land area remained largely stable, with changes of -0.005×10^4 km^2 (-0.04%) and -0.005×10^4 km^2 (-0.04%), respectively. . For grasslands, slight increases were observed in both the ND and SD scenarios, with growth rates of 0.029×10^4 km^2 (+0.06%) and 0.033×10^4 km^2 (+0.06%), respectively. while the WP scenario showed a significant decrease of 1.805×10^4 km^2 (-3.56%), with degraded areas concentrated in the northern Tibetan Plateau and the Ali region. Water bodies expanded most markedly under the WP scenario, increasing by approximately 1.592×10^4 km^2 (+29.05%), primarily distributed in lakes and river basins of the northern Tibetan Plateau; The ND and SD scenarios also showed substantial increases, at 0.620×10^4 km^2 (+11.31%) and 0.618×10^4 km^2 (+11.28%), respectively. Land use for construction showed growth across all scenarios, with the largest increase occurring under the ND scenario at 0.049×10^4 km^2 (+51.14%), primarily located in the Yarlung Tsangpo River valley in southern Tibet and the Huangshui River valley in Qinghai; The WP and SD scenarios increased by 0.035×10^4 km^2 (+36.75%) and 0.031×10^4 km^2 (+32.53%), respectively. Unutilized land decreased in all scenarios, with the largest reduction in the WP scenario at 1.233×10^4 km^2 (-3.62%); the ND and SD scenarios decreased by 0.69×10^4 km^2 (-2.03%) and 0.678×10^4 km^2 (-2.00%), respectively.

Overall, land use changes under all three scenarios reflect the trade-offs between ecological conservation and socioeconomic development in the Qinghai-Tibet Plateau region. Under the Water Conservation Scenario, while water bodies and forest areas significantly increase, the substantial reduction in cropland and grassland may exert pressure on local agricultural production and ecosystems. In contrast, the Natural Development and Sustainable Development Scenarios exhibit relatively balanced land use changes, accommodating both ecological conservation and socioeconomic development needs.

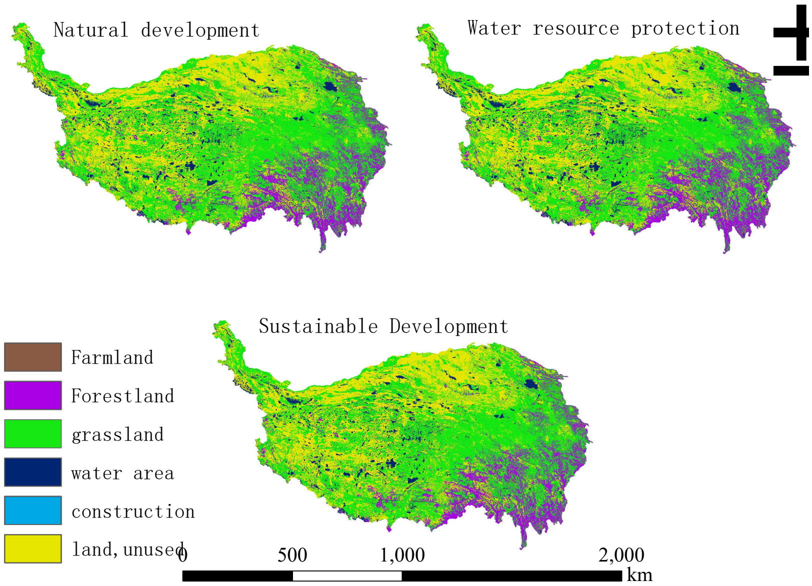

Figure 4. Land Use Distribution Map of the Qinghai-Tibet Plateau Under Different Development Scenarios in 2060

4. Discussion

This study utilized the PLUS model to systematically simulate and analyze land use/land cover change (LUCC) on the Qinghai-Tibet Plateau from 2000 to 2020 and projected land use patterns for 2060 under different scenarios. Results indicate that the plateau's land use structure has remained generally stable over the past two decades, while showing positive trends of slight grassland expansion and a reduction in unutilized land, reflecting the initial success of ecological restoration projects. The limited expansion of forest land, water bodies, and constructed land also indicates the cumulative impact of localized human activities.

Methodologically, the PLUS model demonstrated strong adaptability in simulating the complex topography and heterogeneous landscapes of cold regions, effectively capturing the fragmented changes characteristic of ecological transition zones. The model exhibited robust dynamic explanatory power in characterizing competition and conversion between land types, particularly in simulating spatial responses under multiple policy scenarios.

Regarding driving mechanisms, this study reveals that LUCC on the plateau is jointly regulated by natural factors and human activities, with climate warming and drying alongside ecological engineering implementation being key drivers of changes in grassland and unutilized land. The multi-scenario simulations confirm the nonlinear impacts of land-use transitions on the ecological environment, showing distinct differences and trade-offs in the ecological consequences of different policy pathways.

The study established three scenarios—ND, WP, and SD—corresponding to the governance logics of "development inertia," "ecological priority," and "coordinated balance," respectively. Significant expansion of water bodies and woodlands under the WP scenario, coupled with the corresponding retreat of grasslands, reflects the potential systemic imbalance risks triggered by single-objective policies.

It should be noted that this study has limitations in quantifying policy factors. Rigid constraints such as ecological conservation redlines were not sufficiently spatialized, affecting the model's simulation accuracy in strictly controlled zones. Future research could explore integrating system dynamics with multi-agent models to enhance simulation capabilities for multi-stakeholder behaviors during policy implementation.

In summary, this study employs the PLUS model to reveal fundamental patterns and multi-scenario evolution pathways of land use change on the Qinghai-Tibet Plateau. This approach not only expands the methodological scope for LUCC simulation in high-altitude regions but also provides a scientific basis for regional land-use planning and ecological conservation policy formulation. Future efforts should focus on enhancing the spatial representation of policy-driven factors and integrating higher-resolution remote sensing and socioeconomic data to continuously improve simulation and prediction capabilities for human-land system coupling processes in cold regions.

5. Conclusions

This study employed the PLUS model to reveal the evolution patterns of land use/land cover change (LUCC) on the Tibetan Plateau from 2000 to 2020 and simulated multiple scenarios for the spatial patterns projected to 2060. Key findings include:

(1) Over the past two decades, LUCC exhibited an overall pattern of "stable ecological foundation and continuous structural optimization." Grasslands ($+2.47\times10^4$ km^2) and unutilized land (-3.00×10^4 km^2) emerged as dominant land types. Their significant "mutual expansion and contraction" represents the core structural change in regional LUCC, signifying positive ecosystem succession. The sustained expansion of forest and water bodies alongside the reduction of cropland collectively confirm the leading role of ecological restoration policies in driving regional land use transformation.

(2) Spatial differentiation patterns are governed by hydrothermal-topographic gradients and human activity corridors. LUCC processes exhibit strong spatial dependency aligned with natural geographic patterns: ecological land use changes primarily respond to climate and topographic factors, while the "point-axis" expansion of construction land is strictly constrained by river valleys and transportation corridors, revealing adaptive human choices under harsh environmental conditions.

(3) Multi-scenario simulations clarify differentiated ecological consequences under distinct policy pathways. By 2060, the Natural Development (ND) scenario would trigger disorderly expansion of construction land (+51.14%), compressing ecological space; The Water Protection (WP) scenario significantly enhances water conservation capacity (+29.05% in water bodies) but at the expense of grasslands (-3.56%);

The Sustainable Development (SD) scenario achieves an effective balance between development and conservation while maintaining ecological matrix stability, representing the optimal pathway for ensuring long-term ecological security on the Qinghai-Tibet Plateau.

This study confirms that policy interventions serve as a critical lever for regulating human-land system coupling processes in alpine regions. Future efforts should prioritize sustainable development pathways, leveraging precise territorial spatial management to consolidate and enhance the ecological barrier function of the Qinghai-Tibet Plateau.

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