Multi-scenario simulation of land use change and its impact on ecosystem services in the northeastern edge of the Qinghai-Xizang Plateau, China (Postprint)

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Abstract

The Qinghai-Xizang Plateau (QXP) serves as a crucial ecological barrier in China and Asia, exerting profound influences on global climate and biodiversity conservation. Gannan Tibetan Autonomous Prefecture (hereinafter referred as Gannan Prefecture), located on the northeastern edge of the QXP, represents a fragile alpine ecosystem in which land use change significantly impacts ecosystem services (ESs). This study established a comprehensive framework, utilizing the Patch-generating Land-Use Simulation (PLUS) model coupled with the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model to predict land use patterns under the natural development scenario, cultivated land protection scenario, and ecological protection scenario for Gannan Prefecture by 2030 and evaluated four critical ESs: habitat quality (HQ), water yield (WY), soil retention (SR), and carbon storage (CS). The primary aim is to elucidate the impacts of dynamic land use change on ESs. The results revealed that, from 2000 to 2020, HQ exhibited minimal variation, whereas CS experienced a slight decline. Conversely, WY and SR showed significant improvements. Under the natural development scenario, construction land was projected to increase by 4247.74 hm2, primarily at the expense of forest land. The cultivated land protection scenario anticipated an increase in farmland by 2634.36 hm2, which was crucial for maintaining food security. The ecological protection scenario predicted a notable expansion of forest land, accompanied by a restrained development rate of construction land. The ecological protection scenario also showed an increase in the ecosystem service index (ESI), encompassing 26.07% of the region. Forest land and grassland emerged as the primary contributors to ESs, while construction land substantially impacted WY. Water bodies exhibited minimal contribution to ESs. This study enhanced the understanding of land use change impacts on ESs in fragile and high-altitude ecosystems, offering essential theoretical frameworks and practical direction for forthcoming ecological policy and regional planning endeavors.

Full Text

Preamble

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Multi-scenario Simulation of Land Use Change and Its Impact on Ecosystem Services in the Northeastern Edge of the Qinghai-Xizang Plateau, China

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Abstract: The Qinghai-Xizang Plateau (QXP) serves as a crucial ecological barrier in China and Asia, exerting profound influences on global climate and biodiversity conservation. Gannan Tibetan Autonomous Prefecture (hereinafter referred to as Gannan Prefecture), located on the northeastern edge of the QXP, represents a fragile alpine ecosystem where land use change significantly impacts ecosystem services (ESs). This study established a comprehensive framework utilizing the Patch-generating Land-Use Simulation (PLUS) model coupled with the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model to predict land use patterns under natural development, cultivated land protection, and ecological protection scenarios for Gannan Prefecture by 2030, and evaluated four critical ESs: habitat quality (HQ), water yield (WY), soil retention (SR), and carbon storage (CS). The primary aim was to elucidate the impacts of dynamic land use change on ESs. The results revealed that from 2000 to 2020, HQ exhibited minimal variation, whereas CS experienced a slight decline. Conversely, WY and SR showed significant improvements. Under the natural development scenario, construction land was projected to increase by 4247.74 hm2, primarily at the expense of forest land. The cultivated land protection scenario anticipated an increase in farmland by 2634.36 hm2, which was crucial for maintaining food security. The ecological protection scenario predicted a notable expansion of forest land, accompanied by a restrained development rate of construction land. This scenario also showed an increase in the ecosystem service index (ESI), encompassing 26.07% of the region. Forest land and grassland emerged as the primary contributors to ESs, while construction land substantially impacted WY. Water bodies exhibited minimal contribution to ESs. This study enhanced understanding of land use change impacts on ESs in fragile and high-altitude ecosystems, offering essential theoretical frameworks and practical direction for forthcoming ecological policy and regional planning endeavors.

Keywords: PLUS-InVEST model; ecosystem service; habitat quality; water yield; soil retention; carbon storage; Qinghai-Xizang Plateau

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Introduction

The impact of land use change on ecosystem services (ESs) has become increasingly significant due to intensified global climate change and human interventions, especially in vulnerable high-altitude ecosystems. Ecosystems provide numerous products and services essential for sustaining life and supporting societal frameworks [?]. ESs, which represent the benefits humans gain from ecosystems, serve as a critical link between the natural environment and human well-being [?]. Land use change is a pivotal factor influencing ESs, profoundly impacting Earth's energy balance and biogeochemical cycles. Global phenomena such as urbanization, economic development, and population growth have modified regional spatial organization worldwide, intensifying competition for space and inducing land use changes [?]. These shifts have adversely affected ecosystem structure and functioning, leading to a general decline in ecosystem health and services both locally and globally [?]. Additionally, land use activities and various economic, social, and environmental factors determine changes in agriculture, urban infrastructure, and ecological systems in different regions [?, ?]. Serving as the direct and primary driving force behind dynamic ecosystem shifts, land use change profoundly impacts crucial ecological processes on land, including energy exchange, water cycling, and biogeochemical cycles [?, ?]. Changes in land use types can lead to habitat loss and fragmentation, subsequently affecting species distribution and abundance [?]. Such changes also impact ecosystem physical and biological characteristics [?, ?], exacerbating problems such as water deficiency and soil erosion. Consequently, these alterations pose immediate threats to ecological security, economic development, social stability, and people' s quality of life [?].

Inaccurate assessment of ES poses a significant barrier to identifying the impacts of land use change on ESs and effectively managing ecological environments [?]. Presently, two primary research paradigms exist for quantifying ES levels: the value method and the material quantity method. The value method indirectly quantifies ESs through approaches such as emergy and monetary valuation, whereas the material quantity method involves direct calculation of biophysical quantities. The Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model is a frequently used material quantity method widely employed in complex decision-making processes due to its outstanding efficiency and reliability. Applications include evaluations of ES supply and demand [?, ?, ?], ES vulnerability [?, ?, ?], and ES trade-offs and synergies [?, ?, ?]. Common research methodologies include multiple linear regression [?], the Pressure-State-Response (P-S-R) model [?], emergy analysis [?], scenario simulation [?], and life cycle assessment [?]. Moreover, ES research encompasses a multi-scale analytical framework spanning national [?], provincial [?], municipal [?], urban agglomeration [?], and watershed scales [?], often focusing on ecologically fragile areas and economically developed regions.

Numerous studies evaluating ESs across various spatial scales have integrated land use with ESs. Scholars have explored trends in land use change and their impacts on ESs. For example, Quintas-Soriano et al. [?] investigated how land use changes affected key services in arid ecosystems such as agriculture, water regulation, and tourism. Similarly, Feng et al. [?] developed a framework to examine how land use influenced ESs in terms of structure, function, and dynamics. However, notable gaps remain in model simulation and effect assessment of land use change on ESs. Furthermore, simulations of future scenarios often neglect exploring changes under alternative scenarios in conjunction with national policies, instead focusing solely on natural development trajectories. Models such as the Markov model [?], Cellular Automata model [?], System Dynamics model [?], Future Land Use Simulation (FLUS) model [?], and Conversion of Land Use and its Effects at Small Region Extent (CLUE-S) model [?] provide means to simulate future land use. The Patch-generating Land-Use Simulation (PLUS) model proposed by Liang et al. [?] outperforms other models in excavating the causes of land use change and improving simulation accuracy of spatial patterns, and is widely utilized globally and regionally. Elucidating the nonlinear and complex relationships among land use, ESs, and policies remains an important field for future research.

Considering the constraints of multiple sustainable development goals and the imperative to align with regional development needs, investigating the impact of land use change on ESs is crucial. The QXP ecosystem is highly sensitive and vulnerable due to its unique geography and climate, making it weak in resisting external disturbances; once damaged, recovery becomes extremely challenging [?]. Increased human activities have altered land use patterns and exerted profound, lasting effects on the QXP environment. Located in this critical region, Gannan Tibetan Autonomous Prefecture, Gansu Province, China (hereinafter abbreviated as Gannan Prefecture), holds significant importance in the “Chinese Water Tower” region and possesses substantial ES function value. The region’ s environmental status is unstable, characterized by intensive anthropogenic impact and the requirement for ecosystem preservation. Thus, the interaction between global environmental changes and local human activities has caused significant ecological changes that have affected the Yellow River Basin and spread consequences throughout Northwest China. In this study, we utilized the PLUS model to forecast land use patterns under three scenarios (natural development, cultivated land protection, and ecological protection) in Gannan Prefecture for 2030. Additionally, we adopted the InVEST model to quantify four ESs—habitat quality (HQ), water yield (WY), soil retention (SR), and carbon storage (CS)—from 2000 to 2030, incorporating land use dynamics as a key consideration. The objectives were threefold: first, to map temporal and spatial variations in ES functionalities in Gannan Prefecture from 2000 to 2020; second, to model and contrast the impacts of diverse future land use scenarios through 2030; and third, to evaluate how land use change impacts ESs, aiming to enhance synergy between economic growth and ecological sustainability in ecologically sensitive, high-altitude regions. This study integrated multi-source data and methodologies to predict land use change under various future scenarios, forecast trends in ES variations, and ultimately identify potential ecological risks and issues. These findings can serve as the bedrock for formulating optimized land use allocation strategies and implementing ecosystem management, while providing empirical evidence and decision-making assistance for reconciling economic development with environmental conservation in ecologically vulnerable, high-altitude regions.

Study Area

Located on the northeastern edge of the QXP and southwestern Gansu Province, Gannan Prefecture (33°06 -36°10 N, 100°46 -104°44 E) serves as a transitional area connecting the QXP, the Loess Plateau, and the Longnan Mountains. It adjoins the Aba Tibetan and Qiang Autonomous Prefecture in Sichuan Province to the south and the Huangnan Tibetan Autonomous Prefecture and Golog Tibetan Autonomous Prefecture in Qinghai Province to the southwest. Within Gansu Province, Gannan Prefecture is bordered by Longnan City, Dingxi City, and Linxia Hui Autonomous Prefecture from east to north. Administratively, Gannan Prefecture consists of one city and seven counties: Hezuo City, Xiahe County, Luqu County, Maqu County, Lintan County, Jone County, Tewo County, and Zhugqu County [Figure 1: see original paper]. With elevations ranging from 1204 to 4688 m, generally ascending toward the northwest and declining toward the southeast, the prefecture covers an area of 4.50$×$106 hm2. The northwest is characterized by alpine meadows and pastures, making it one of China' s five major pastoral regions. The eastern part features rolling hills, while the southern section is predominantly occupied by mountainous terrain of the Minshan and Diego mountains. The climate is predominantly continental and seasonal, with an annual average temperature around 3°C and large regional temperature differences. Annual precipitation ranges between 400 and 800 mm, concentrated mainly in summer. These environmental conditions contribute to the region' s ecological significance within the Yellow River Basin. Protecting the ecological landscape in Gannan Prefecture is vital for water and soil conservation, climate regulation, and biodiversity preservation, thereby supporting regional socio-economic progress. The prefecture is home to various ethnic minorities, with agriculture and livestock farming as primary income sources. Economic development and increased urban growth have exacerbated ecological vulnerabilities and intensified conflicts between human activities and environmental conservation [**?**, **?**], making it crucial to evaluate ESs and examine linkages between land use and ecosystem benefits to promote ecological preservation and sustainable development.

Data Sources

Land use data were obtained from the Resource and Environmental Science and Data Center of the Chinese Academy of Sciences (https://www.resdc.cn/) and converted from vector to raster format with 30 m resolution. Meteorological elements including precipitation, temperature, and potential evapotranspiration were interpolated from daily data recorded at regional weather stations, also provided by the same institution. Root-restricting layer depth data were obtained from a high-resolution (100 m) Chinese soil depth map by Yan et al. [**?**]. Plant-available water capacity (PAWC) was estimated using a non-linear fitting model developed by Zhou et al. [**?**], incorporating inputs from the Harmonized World Soil Database (HWSD) supplemented with soil composition metrics from the National Tibetan Plateau Data Center (https://data.tpdc.ac.cn/). The digital elevation model (DEM), necessary for topographical attributes like slope and orientation, was sourced from the Geospatial Data Cloud (https://www.gscloud.cn/). The normalized difference vegetation index (NDVI) was calculated using the maximum value composite method from monthly datasets provided by NASA (https://www.nasa.gov/). All raster datasets were converted to the Krasovsky_{{{1940}}_{{Albers}}} coordinate system to align with Gannan Prefecture' s administrative boundaries. Additionally, gross domestic product (GDP) and population density data were acquired from the Resource and Environmental Science and Data Center. Details about highways, water systems, and government premises were obtained from the National Geographic Information Resource Catalog Service System (https://www.webmap.cn/main.do?method=index) and processed to calculate Euclidean distances.

Analysis Methods

The research methodology was structured around four key phases. Initially, it involved gathering and processing data. In the second phase, we analyzed land use patterns and changes through land use transition matrices and spatial analyses using ArcGIS v.10.4 (Eris, Redlands, California, USA). Next, we utilized the PLUS model to simulate and predict future land use scenarios. The third phase involved evaluating historical ESs through the InVEST model and forecasting variations under various scenarios based on simulated land use data. Finally, this study explored the mechanisms through which land use change impacts ESs, with outcomes employed to develop specific policy recommendations and actions [Figure 2: see original paper].

Land Use Transition Matrix

The land use transition matrix is a core component of the Markov model, providing a quantitative description of land use change across different time dimensions and categories. This matrix systematically analyzes area transitions between various land use types over specified time intervals, thereby elucidating change dynamics [?]. The model can be expressed mathematically as:

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

where S is the land area (hm2); a is the land use type at the beginning of analysis; b is the land use type at the later stage; and n is the total number of land use categories. Values on the matrix diagonal indicate changes in area of the same land use type across different time periods.

Scenario Setting

The PLUS model is a newly developed Cellular Automaton model built upon the FLUS model, integrating the rule mining framework of the Land Expansion Analysis Strategy (LEAS) and the Cellular Automaton based on Random Seed and multi-type patches (CARS) model. This integration enhances the ability to uncover various driving factors behind land use change while improving simulation accuracy at the patch level [?]. For driving land use change, this study considered various spatial variables including natural factors (elevation, slope, annual precipitation, and annual average temperature), transportation and location factors (distance from government premises, highways, and water bodies), and socio-economic factors (GDP and population density).

Guided by the study area' s particular circumstances and prevailing literature [?, ?], we established three distinct simulation scenarios, each characterized by specific land use needs, neighborhood weights, conversion rules, and constraint conditions:

Natural Development Scenario: Assumes past land use change patterns will continue without hindrances to conversion between land use types or restrictive policy measures. Forecasts rely on conversion probabilities derived from 2010-2020 data.

Cultivated Land Protection Scenario: Areas important for agriculture are categorized as limited for conversion to ensure these plots are not taken over by other land use types. The transfer matrix probabilities are adjusted to decrease farmland-to-construction land conversion by 50.00% and increase conversion of other land use types into farmland by 20.00%.

Ecological Protection Scenario: Based on the "Ecological Protection and High-Quality Development Plan of the Yellow River Basin in Gansu Province," land use conversion restricted zones include natural reserves and water bodies. This strategy aims to reduce forest land and grassland conversion to other land use types, specifically decreasing transformation of forest land and grassland into construction land by 60.00% and 40.00%, respectively, while reducing farmland-to-construction land conversion by 20.00%.

Model Validation

Land use projection accuracy was evaluated using the Kappa statistic and overall accuracy. A Kappa statistic higher than 0.80 proves simulation reliability. Using 2010 data as baseline, the PLUS model estimated land use patterns through 2020, with accuracy verified by comparing projections to actual data. The model demonstrated substantial precision with a Kappa statistic of 0.85 and overall accuracy of 0.89, laying the groundwork for forecasting land use trends through 2030.

Habitat Quality Assessment

HQ is evaluated by integrating landscape sensitivity assessments with external threat intensity, serving as a critical indicator for biodiversity health [**?**]. Since various habitat types respond differently to environmental pressures, sensitivity analyses tailored to specific threat magnitudes are crucial for accurate HQ assessment. The formula is as follows [**?**]:

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

where Q_{xj} is the habitat quality of habitat type j in grid cell x; H_j is the habitat suitability of habitat type j; D_{xj} is the habitat degradation degree to habitat type j in grid cell x; and k and z are the half-saturation constant and default parameter in the model, respectively.

Water Yield Assessment

WY serves as an effective indicator for evaluating regional water supply capacity [**?**]. The InVEST WY assessment model employs the Budyko water-energy balance hypothesis to calculate each grid cell' s WY by subtracting actual evapotranspiration from precipitation. The formulas are as follows [**?**]:

$$WY_x = \left(1 - \frac{AET_x}{P_x}\right) \times P_x$$

$$\frac{AET_x}{P_x} = \frac{1 + \omega_x \times \frac{PET_x}{P_x}}{1 + \omega_x \times \frac{PET_x}{P_x} + \frac{P_x}{PET_x}}$$

$$\omega_x = Z \times \frac{AWC_x}{P_x}$$

where WY_x is the annual water yield of grid cell x (mm); AET_x is the annual actual evapotranspiration of grid cell x (mm); P_x is the annual precipitation of grid cell x (mm); PET_x is the potential evapotranspiration of grid cell x (mm); ω_x is a non-physical empirical parameter related to natural climate and soil properties; AWC_x is the available water capacity for plants within grid cell x (mm); and Z is a seasonal constant characterizing precipitation patterns within the study area.

Soil Retention Assessment

SR represents the capacity of natural systems to provide soil preservation functionalities, quantified using the universal soil loss equation. The formulas are as follows [**?**]:

$$SR = R \times K \times LS \times (1 - C \times Q)$$

where SR is the soil preservation capacity (t/(hm2 · a)); R is the rainfall erosivity factor (MJ · mm/(hm2 · h · a)); K is the soil erodibility factor (t · h/(MJ · mm)); LS is the slope length-slope steepness factor; C is the crop or vegetation management factor; and Q is the soil and water conservation measure factor. In this study, Q was designated as: 0.40 for farmland, 0.60 for forest land, 0.50 for grassland, 0.00 for water body, 1.00 for construction land, and 0.00 for unutilized land [**?**].

$$C = \exp\left(-\beta \times \frac{NDVI}{NDVI_{\max} - NDVI_{\min}}\right)$$

where β is a parameter; $NDVI$ is the Normalized Difference Vegetation Index; $NDVI_{\min}$ is the minimum NDVI value; and $NDVI_{\max}$ is the maximum NDVI value.

Carbon Storage Assessment

CS evaluations combine land use data with measurements across four carbon reservoirs (aboveground carbon density, underground carbon density, soil carbon density, and dead organic matter carbon density), enabling thorough evaluation of current conditions and temporal variations in landscape carbon storage capacity [**?**]. The formulas are:

$$C_i = C_{i\text{-above}} + C_{i\text{-below}} + C_{i\text{-soil}} + C_{i\text{-dead}}$$

$$C_{\text{total}} = \sum_{i=1}^{n} C_i \times S_i$$

where C_i is the aggregate carbon density for land use type i (t/hm2); $C_{i\text{-above}}$ is the aboveground vegetation carbon density (t/hm2); $C_{i\text{-below}}$ is the live root carbon density beneath ground (t/hm2); $C_{i\text{-soil}}$ is the soil carbon density (t/hm2); $C_{i\text{-dead}}$ is the litter carbon density (t/hm2); C_{total} is the total carbon storage (t); and S_i is the total area occupied by land use type i (hm2).

Ecosystem Service Index Calculation

Developing an ESI allows representation and quantification of cumulative impacts from various ESs. Since each ES indicator varies in attributes, scale, and units, direct comparison is not feasible. A numerical normalization procedure addresses these disparities and ensures comparability among indicators [**?**]. The ESI offers a comprehensive view of ecosystem conditions across regions, making it useful for governmental organizations developing planning strategies. The methodology is:

$$ESN_{rx} = \frac{ES_{rx} - ES_{\min}}{ES_{\max} - ES_{\min}}$$

$$ESI_x = \sum_{r=1}^{m} ESN_{rx}$$

where ESN_{rx} is the normalized value of the rth ecosystem service within grid cell x; $ES_{\max}$ and $ES_{\min}$ are the maximum and minimum ES values across all grid cells; ESI_x is the ecosystem service index for grid cell x; and m is the total number of ecosystem service types.

We analyzed spatial ESI variation across scenarios by calculating differences from 2020 to 2030, classifying changes using the natural breaks method: moderate decline (< -0.280), slight decline (-0.280 to -0.100), basically unchanged (-0.100 to 0.008), slight increase (0.008 to 0.270), moderate increase (0.270 to 0.450), and obvious increase (>0.450). The land use transition matrix identifies change patterns, aiding land managers in understanding distribution and clustering of changes. Using ArcGIS zoning statistical tools, various land use transitions were classified to extract mean values and variances of ESI changes triggered by different land use alterations, assisting in grasping spatial diversity of ESI changes and crafting targeted zoning policies [**?**].

Land Use Characteristics

Grassland and forest land were the predominant land covers in the region. In 2020, grassland accounted for 56.77% of total area, while forest land accounted for 30.72%. Unutilized land and farmland represented 7.02% and 4.30%, respectively. Water bodies covered 0.70%, with construction land being the least extensive at 0.46%. Grassland, primarily located in Maqu, Xiahe, and Luqu counties, formed the core pastoral areas and was essential to the QXP’ s ecological barrier. Forest land was abundant in Tewo, Jone, Zhogqu, and Xiahe counties, indicating significant forest resources. Unutilized land, mainly in Maqu, Tewo, and Luqu counties, constituted 80.36% of the prefecture’ s unutilized area. Farmland was predominantly located along rivers in Lintan, Zhugqu, and Jone counties, where water conservation projects were vital for improving crop yields. The region featured extensive water systems, with water bodies in Maqu, Luqu, and Zhugqu counties accounting for 86.50% of total water area. Construction land, although limited, was concentrated around county towns and key transport routes, with Xiahe and Lintan counties having the highest concentrations at 20.27% and 18.90%, respectively [Figure 3: see original paper].

The chord diagram indicated that from 2000 to 2020, land use changes were primarily characterized by reciprocal conversions among grassland, forest land, and farmland [Figure 4: see original paper]. During this period, grassland experienced a net increase of 2518.24 hm2, primarily due to conversion of farmland and unutilized land into grassland, followed by conversion of grassland into forest land. Meanwhile, farmland decreased by 10,788.81 hm2, mainly transitioning into grassland and construction land. This reduction resulted largely from ecological land retirement strategies and infrastructure development, which also led to a construction land increase of 3965.52 hm2. Forest land saw a net increase of 4481.00 hm2, mainly from grassland conversions. Environmental conservation efforts including reforestation, grassland rehabilitation, and wetland protection facilitated transformation of unutilized land into ecological zones, resulting in a 7750.46 hm2 decrease in unutilized land, primarily converted into grassland and water bodies. Rapid urban expansion also contributed to conversion of farmland near urban areas into construction land, leading to a significant net increase of 6763.64 hm2 in built environments. Furthermore, water bodies expanded by 5045.92 hm2, primarily due to conversion of grassland and previously unutilized land.

Land Use Multi-scenario Simulation

Figure 5 illustrates projected land use scenarios for Gannan Prefecture by 2030. These projections suggest that overall land distribution patterns might mirror trends observed from 2000 to 2020, yet with discernible regional variations. Under natural development, the greatest reduction would pertain to farmland, projected to shrink by 2726.64 hm2 compared to 2020, followed by a 1983.12 hm2 decrease in grassland. Expansions were expected in construction land, water bodies, and unutilized land, increasing by 4247.74, 532.48, and 438.02 hm2, respectively. Construction land would undergo the most extensive expansion, primarily through transformation of forest land. In contrast, under cultivated land protection, increases were anticipated in farmland, water bodies, construction land, and unutilized land, while decreases were projected for forest land and grassland. Farmland would see the largest growth, increasing by 2634.36 hm2 as development encroached upon forest land and grassland. Finally, the ecological protection scenario predicted a considerable rise in forest land, up by 3388.45 hm2, largely converting from unutilized land and farmland. Although construction land was expected to continue growing under this scenario, the expansion rate was forecasted to decelerate [Figure 5: see original paper].

Spatio-temporal Characteristics of ES from 2000 to 2020

From 2000 to 2020, HQ in Gannan Prefecture remained stable, averaging 0.7543 in 2000, 0.7562 in 2010, and 0.7553 in 2020. Analysis showed that 35.00% of the region achieved high HQ, while around 50.00% reached a relatively high level. Areas of relatively low and low HQ each constituted less than 5.00%, indicating generally favorable conditions. Spatial analysis revealed significant variance, with a "high-low-high" pattern from southeast to northwest. High HQ areas included forest land and grassland, whereas low-value areas were mainly associated with farmland and construction land, particularly in Lintan County where human activities had strong influence. The average HQ value surpassed 0.6000, indicating a consistent improvement trend [FIGURE:6a1-a3].

Gannan Prefecture experienced a significant WY increase from 2000 to 2020. The lowest recorded WY was 111.02 mm in 2000, while the highest was 229.20 mm in 2020, attributed to higher precipitation. Spatially, WY decreased from southwest to northeast, with the highest yields in Maqu County and lower yields in Zhogqu and Lintan counties. Lower WY in grasslands and forest lands was due to higher evaporation compared to construction lands [FIGURE:6b1-b3].

SR showed marked improvement from 2000 to 2020, with values of 74.42 t/hm2 in 2000, 87.72 t/hm2 in 2010, and 128.16 t/hm2 in 2020. This enhancement was partly due to increased vegetation coverage, which stabilizes soil, reduces erosion, and improves SR. Spatially, high SR values were concentrated in the southeast, particularly in Tewo and Zhugqu counties with extensive forest land and grassland coverage. Lower SR values were noted in the southwest, characterized by extensive unutilized land [FIGURE:6c1-c3].

CS experienced a marginal decline from 26.45$×10 < *sup* > 6 < /*sup* > *tin*2000*to*26.34×$106 t in 2020. Carbon density followed a similar trend, recorded at 7.22 t/hm2 in 2000, slightly dropping to 7.21 t/hm2 in 2010, and reaching 7.19 t/hm2 in 2020. Urban expansion into agricultural land primarily accounted for this reduction. Spatially, higher CS was found in the southeast, diminishing toward the northwest. Forest land and grassland in Hezuo City, Zhugqu County, and Tewo County maintained elevated carbon levels, in contrast to Maqu County, where 62.60% of the area remained unutilized with sparse vegetation, resulting in lower CS [FIGURE:6d1-d3].

Changes in ES under Multiple Scenarios from 2020 to 2030

Analysis of ES changes from 2020 to 2030 under three scenarios—natural development, cultivated land protection, and ecological protection—is presented in Figure 7. Compared to 2020, HQ revealed a declining trend across all scenarios, with natural development showing the most significant reduction due to swift urban expansion encroaching upon natural habitats. For WY, spatial distribution generally aligned with these scenarios, being higher in the west and south compared to the east and north. Conversely, Zhugqu and Jone counties in the southeast exhibited lower precipitation due to geographical and climatic factors. Regarding SR, notable spatial disparities existed, with Tewo and Zhugqu counties identified as high-value areas. However, future simulations predicted considerable SR reduction risk in these regions, potentially linked to further urban sprawl and ecological degradation. Across all scenarios, CS demonstrated relatively minor fluctuations, indicating a certain level of stability [Figure 7: see original paper].

Impact of Land Use Change on ES

From 2000 to 2020, Gannan Prefecture experienced diverse land use shifts [Figure 8: see original paper]. In Tewo County, ecosystem functions were mainly affected by transitions from grassland to forest land and from farmland to grassland. In Hezuo City, predominant changes involved converting farmland into grassland and construction land. Lintan County saw reciprocal transformations between farmland and grassland. In Luqu County, primary shifts were from grassland to forest land and construction land, with additional conversions of unutilized land into water bodies. Maqu County mainly changed from unutilized land to grassland, followed by transitions from grassland to forest land. Xiahe County showed dynamics similar to Tewo County, with frequent interchanges among grassland, forest land, and farmland. In Zhugqu County, the primary transformation was conversion of farmland to grassland. In Jone County, predominant shifts included transitions from farmland to grassland, from grassland to forest land, and to a lesser extent, from farmland to construction land.

In ES assessment, forest land, grassland, and water bodies played pivotal roles, contributing 28.17%, 22.33%, and 24.43% to overall HQ, respectively, from 2000 to 2020 [Figure 9a: see original paper]. Conversely, construction land yielded the most WY at 40.16%, surpassing forest land, grassland, and water bodies due to lower evaporation rates in built environments. Regarding SR, forest land was notable with a contribution of approximately 29.65%. Farmland also significantly contributed to CS, ranking just behind forest land, and its conversion to construction land greatly impacted CS reduction. Overall, while forest land and grassland were essential for maintaining ES, construction land strongly influenced WY, and water bodies provided lesser yet significant contributions.

Land use transformations significantly impacted ES functionality. Forest land was the most significant contributor, and transitions toward forest land from other types tended to enhance benefits notably. For instance, converting construction land to forest land could increase ESs by approximately 39.70%, while transforming farmland into forest land would result in about 10.80% increase [Figure 9b: see original paper]. In contrast, construction land and unutilized land offered minimal ES benefits. Thus, replacing grassland, forest land, farmland, or water bodies with unutilized land or construction land led to marked ES reductions, decreasing by 38.30% and 41.80%, respectively, when forest land was converted to construction land or unutilized land.

The gradient effect of land use change on ES is evident [**?**], and alterations in land use structure are crucial to ecological security. At altitudes between 1000 and 2000 m, significant shifts included farmland reduction and construction land increase, indicating loss of high-quality agricultural land. As altitude increased, forest land and grassland became predominant. Above 2000 m, grassland occupied a larger proportion than any other land use type [Figure 10: see original paper]. Differences in ES across land use types were marked [Figure 11: see original paper]. Forest land and grassland more effectively enhanced HQ across different altitudes than other types. WY was higher from construction and unutilized lands compared to other types at various altitudes. Forest land was paramount in contributing to SR, while farmland, forest land, and grassland consistently contributed to CS without notable variation across altitudes. Crafting land utilization policies and ecological stewardship approaches that accommodate varied consequences of land use are crucial for maximizing ecological functionality.

Impact of Different Development Patterns on ES

The baseline ESI in 2020 was 0.591, with projections indicating increases to 0.626, 0.638, and 0.651 under natural development, cultivated land protection, and ecological protection scenarios, respectively, suggesting potential ES level improvement. Regions with high ESI, such as Tewo, Jone, and Zhugqu counties, benefited from extensive forest land and grassland coverage. In contrast, Xiahe County, western Maqu County, and border areas of Jone and Tewo counties showed lower ESI due to challenging topography and sparse vegetation. Under natural development, notable ESI decline was observed due to increased construction land. The cultivated land protection scenario showed relative stabilization across 74.80% of the area. In the ecological protection scenario, areas experiencing ESI increase comprised the largest share at 26.07%, with minimal regions undergoing severe or moderate degradation [Figure 12: see original paper].

Changes in ES Caused by Different Land Use Types

This study comprehensively examined the intricate relationship between land use dynamics and ESs in Gannan Prefecture. Findings revealed significant spatio-temporal characteristics of ESs from 2000 to 2020. Specifically, except for a slight CS decline and stable HQ, WY and SR exhibited upward trends. The notable WY increase was primarily attributed to dual influences of climate change and ecological policies. On one hand, intensified ecological conservation strategies and enhanced vegetation cover improved water storage and retention capabilities [?]. On the other hand, increased annual precipitation directly facilitated water recharge. Meanwhile, SR enhancement was mainly due to the "Grain for Green" program, where vegetation roots stabilized soil and significantly reduced erosion risk [?]. In contrast, the slight CS decline was primarily caused by rapid construction land expansion encroaching upon farmland, driven by urbanization. Although HQ remained stable overall, localized degradation was observed, reflecting profound human activity impacts. Land use simulations for 2030 indicated that under ecological conservation, ESI reached its highest level while HQ showed slight decline, demonstrating that ESI, as a comprehensive evaluation index through its internal weight balancing mechanism, could reflect complex relationships among various ESs [?, ?]. For instance, improvements in WY and SR may have partially compensated for localized habitat degradation, highlighting the complexity of ES interactions [?].

This study further analyzed impacts of land use type conversion on ESs. Forest land increase, particularly due to effective implementation of ecological restoration measures such as the "Grain for Green Program," significantly enhanced ESs. Transition from construction land to forest land contributed notably to ES improvement with a 39.7% increase. However, converting forest land to construction land reduced ESs by 38.3%. Similarly, disorderly expansion of unutilized land decreased ESs by 41.8%. These changes reflect the importance of prioritizing ecological conservation during urbanization to achieve coordinated economic, social, and environmental development [?]. This study explored cascading effects among "land use change-ecosystem services" within a multi-scenario simulation framework. Under ecological conservation, effectively restricting disorderly construction land expansion and promoting forest land restoration achieved synergistic ES enhancement. In contrast, under natural development, conflict between farmland reduction and disorderly construction land expansion significantly exacerbated tensions between economic development and ecological conservation. Quantitative analysis of impacts from different land use conversions provides a reference for formulating scientifically reasonable land use policies and implementing effective ecological conservation measures.

Implications for Land Use Management

This study identifies diverse impacts of land use change types on ESs, providing decision-making support for determining land development intensity while balancing economic development and ecological conservation [?, ?]. Land use change is driven not only by natural conditions but also by rapid construction land expansion during urbanization and transformation of agricultural production methods [?, ?]. Issues such as disorderly construction land expansion, farmland resource tension, and grassland degradation in Hezuo City and Tewo County all impacted ESs. Frequent conversion between farmland and grassland in Lintan County during agricultural restructuring might reduce ESs. Additionally, Luqu and Maqu counties faced challenges in water resource management and grassland protection, while Xiahe, Zhugqu, and Jone counties exhibited complex relationships between ecological protection and agricultural development. The sharp increase in land demand during urbanization also highlights discord between urban planning and ecological protection [?]. Multi-scenario simulation results further emphasized the urgency of future land use management. Under natural development, farmland and grassland reduction along with construction land encroachment on forest land indicates potential ES decline. Conversely, while ecological protection can promote forest land increase, ongoing construction land expansion remains an urgent issue. Although cultivated land protection can alleviate farmland reduction trends, it may also trigger new ecological issues.

Future macro-control over land use should be strengthened to ensure scientific and forward-looking policies tailored to each region' s ecological characteristics [?, ?]. Hezuo City should clearly define farmland protection boundaries, strictly controlling construction land expansion to alleviate farmland resource tension. Tewo County should establish compensation mechanisms for farmland and grassland conversion, promote renovation of inefficient forest land, designate ecological resettlement areas, and reduce human activity interference in the forest-grassland ecotone. Lintan County should actively promote sustainable agricultural techniques such as crop rotation and intercropping to improve soil quality and ESs. Luqu and Maqu counties must enhance water resource management and implement scientific grazing systems. Xiahe County can explore integrated forestry-grassland management models to facilitate conversion of ecological products into economic value. Zhogqu County should prioritize engineered conversion of farmland into grassland, improve slope runoff harvesting systems, and establish mechanisms for withdrawing construction land in geological disaster areas. Jone County needs to strictly enforce ecological reviews for farmland-to-construction land conversion and develop industrial chains for the forest understory economy.

Limitations and Prospects

This study presented a novel framework amalgamating the PLUS-InVEST model, enhancing ability to simulate and assess land use transformations and supporting detailed exploration of how these changes affect ESs alongside their spatial and temporal variations. However, difficulty in obtaining high-precision data over long time series inevitably affects analysis results due to data resampling [?]. The PLUS model predicts future trends based on historical land use change [?], but external factors such as climate change and policy interventions may significantly influence actual conditions [?]. Moreover, ES change mechanisms are complex, resulting from multiple factor interplay [?]. Model uncertainty and parameter setting sensitivity can also lead to evaluation result deviations [?]. Additionally, while ES types are diverse, this study focused only on four main service types, which may not fully capture overall ecosystem state. Furthermore, land use change impacts on ES exhibit scale effects, while this study examined the issue solely from a raster scale. Future research should emphasize deep integration of high-precision remote sensing and ground-measured data to enhance data timeliness and spatial resolution, thereby improving simulation efficiency and accuracy. It is also necessary to construct a comprehensive dynamic coupling model systematically integrating climate change, socio-economic development trends, and policy interventions. Additionally, establishing unified ES evaluation standards can help reduce assessment discrepancies and uncertainties, enhancing scientific rigor and comparability. Future directions should adopt a more comprehensive multidimensional perspective, focusing not only on direct impacts of land use change on ESs but also exploring indirect effects, cumulative impacts, and ecosystem resilience, disturbance resistance, and recovery capabilities under different land use patterns.

Conclusions

This study employed the PLUS model to project 2030 land use configurations under multiple scenarios and evaluated ESs—HQ, WY, SR, and CS—in Gannan Prefecture from 2000 to 2030. Analysis of land use dynamics produced several pivotal findings: grassland and forest land dominated the landscape, covering 56.77% and 30.72% of total area, respectively. From 2000 to 2020, CS experienced slight decline, HQ remained largely stable, and WY and SR showed positive trends. Under natural development scenarios, construction land expansion was particularly pronounced, encroaching on ecological lands and reducing CS and SR. Under cultivated land protection, farmland area expanded by 2,726.64 hm2, significantly bolstering food security but affecting regional HQ due to intensified human activities. The ecological protection scenario saw notable forest land increase with slower construction activity, substantially improving HQ, SR, and CS.

Forest land and grassland primarily enhanced ESs, whereas construction land significantly contributed to WY. Ecological protection scenarios significantly optimized ESs in Gannan Prefecture, achieving an average ESI value of 0.65, underscoring the core value of adopting an eco-priority strategy for sustainable development of plateau ecological barrier regions. Future research should adopt a more diversified approach, focusing not only on integrating various land use scenarios to comprehensively understand compound effects on ES functionalities, but also emphasizing strategic land use planning and sustainable management that incorporate high-precision data integration, dynamic coupling models, and comprehensive evaluation standards. These efforts are crucial for effectively harnessing and enhancing ecosystem multifaceted benefits.

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