Spatiotemporal Evolution and Prediction of Carbon Storage in Xinjiang Based on the PLUS-InVEST Model (Postprint)

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Abstract

In the context of the “dual carbon” goals, investigating the spatiotemporal evolution of carbon storage and future scenario predictions is of great significance for maintaining ecological balance, promoting high-quality regional development, and achieving the “carbon neutrality” objective. As an ecologically fragile and climate-sensitive region, simulating past and future land use changes and carbon dynamics in Xinjiang contributes to effective formulation of emission reduction strategies and enhanced ecosystem restoration. Based on sustainable development theory, this study couples the PLUS-InVEST model to comprehensively evaluate land use changes in Xinjiang from 1990 to 2050 and their response in carbon storage. The results demonstrate: (1) From 1990 to 2020, Xinjiang’ s land use was dominated by unused land and grassland, accounting for 67% and over 23% of the total land area, respectively. Unused land and grassland exhibited a year-by-year decreasing trend, while all other land use types showed an increasing trend. (2) Grassland is the primary contributor to carbon storage in Xinjiang, and grassland degradation constitutes the main cause of carbon storage loss, with grassland degradation from 1990 to 2020 resulting in a carbon storage loss of 224.16 t. (3) Under the 2050 ecological protection scenario, carbon storage increases by 6.19\$$\times 10^{7} t; undertheeconomy - priorityscenario, carbonstoragelossreaches 3.52\times$\$10^7 t. Through quantitative evaluation of land use changes in Xinjiang over the past and future 30-year period and their impacts on carbon storage, this paper provides reliable reference materials and accurate data support for land management decision-making in Xinjiang.

Full Text

Spatiotemporal Evolution and Prediction of Carbon Storage in Xinjiang Using the PLUS-InVEST Model

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Abstract

Under the "dual carbon" background, investigating the spatiotemporal evolution of carbon storage and future scenario predictions is of great significance for maintaining ecological balance, promoting high-quality regional development, and achieving the "carbon neutrality"goal. As an ecologically fragile and climate-sensitive region, simulating past and future land use changes and carbon storage in Xinjiang can support the effective formulation of emission reduction strategies and ecosystem restoration efforts. Based on sustainable development theory, this study integrates the PLUS-InVEST model to comprehensively assess land use changes in Xinjiang from 1990 to 2020 and their impacts on carbon storage, with predictions through 2050. The results indicate that: (1) From 1990 to 2020, Xinjiang's land use was dominated by unused land and grassland, accounting for over 67% and 23% of the total land area, respectively. Both categories showed a decreasing trend, while other land types exhibited an increasing trend. (2) Grassland is the primary contributor to carbon storage in Xinjiang, and grassland degradation is the main cause of carbon storage loss, with degradation causing a carbon storage loss of 224.16 t between 1990 and 2020. (3) By 2050, under the ecological protection scenario, carbon storage is projected to increase by 6.19×10^{7} t, while under the economic priority scenario, it is expected to decrease by 3.52×10^{7} t. Through quantitative evaluation of past and future land use changes and their impacts on carbon storage, this study provides reliable reference materials and accurate data support for Xinjiang' s land management decision-making.

Keywords: land use change; carbon storage; PLUS model; InVEST model

1 Introduction

Under the background of global climate change, research on terrestrial ecosystem carbon storage has become a key scientific issue for achieving the "carbon neutrality" goal [1-3]. Climate change leads to alterations in land use patterns, which directly impact carbon storage [4-6]. As China' s largest arid region, Xinjiang features a fragile ecological environment and sensitive climate response, with carbon storage changes that differ significantly from humid regions and exhibit distinct regional characteristics [7]. In recent years, Xinjiang' s land use pattern has undergone transformations through grassland degradation and oasis expansion, thereby affecting regional carbon balance [8-10]. Therefore, investigating the impact of land use change on carbon storage in Xinjiang is crucial for fully understanding carbon cycling processes in arid regions.

Numerous scholars have conducted related research in the Xinjiang region. Zhang et al. [11] used the InVEST model to explore the impacts of vegetation cover and urbanization on carbon storage in the urban agglomeration on the northern slope of the Tianshan Mountains. Huang et al. [12] evaluated the spatiotemporal patterns of carbon storage in the Turpan-Hami Basin. Yang et al. [13] investigated the past and future spatiotemporal evolution of carbon storage in the Urumqi-Changji region of Xinjiang. Fu et al. [14] conducted scenario prediction analysis of carbon storage in the Tarim River Basin, finding that future grassland degradation is the main cause of carbon storage reduction.

Currently, research on terrestrial ecosystem carbon storage mainly includes field monitoring [15], remote sensing inversion [16], and model simulation [17]. Among these methods, the InVEST model can calculate carbon storage based on carbon pool data and reveal spatiotemporal changes in carbon storage. This model is simple to operate, has flexible parameters, and can obtain accurate carbon storage simulation results [18]. The PLUS model can clearly demonstrate the driving factors of various land use changes, thereby enabling scientific simulation of future land use changes under different scenarios [19]. The coupling of these two models can achieve carbon storage simulation for study areas under past and future scenarios.

As China' s largest arid region and the core area of the "Belt and Road" Initiative, Xinjiang' s land use change and carbon storage dynamics research holds important theoretical and practical significance. The region features a typical mountain-desert ecosystem pattern. Under the dual pressures of climate change and human activities, Xinjiang' s land use types have undergone tremendous transformations [20]. What impact does this transformation have on the regional carbon storage pattern? What is its mechanism? These scientific questions remain unclear. Currently, as the world' s largest carbon emitter, China faces severe challenges in implementing scientific emission reduction measures. Xinjiang, as a typical arid region ecosystem, holds a strategic position in the national ecological security pattern. Particularly under the "dual carbon" target background, how to coordinate the relationship between economic development and ecological protection, and scientifically assess the impact of land use change on carbon storage, has become a key issue urgently needing resolution for regional sustainable development. Therefore, this study constructs a PLUS-InVEST model framework to systematically analyze the impact of land use change on carbon storage in Xinjiang from 1990 to 2020, and predict carbon storage response characteristics under three land use scenarios (natural development, ecological protection, and economic priority) for 2050. The research results will not only provide theoretical innovation for carbon cycle research in arid region ecosystems but also offer scientific support for regional land use optimization decisions, enhancement of ecosystem carbon sink functions, and achievement of national “dual carbon” targets.

2 Materials and Methods

2.1 Study Area Overview

Xinjiang (34.42°-49.17°N, 77.66°-99.38°E) is located in the hinterland of the Eurasian continent, deep in the inland area of northwestern China, covering an area of 1.66$×10^{6}$ km^2, which accounts for one-sixth of China’ s total land area [21]. The Altai, Tianshan, and Kunlun mountain ranges surround the Junggar and Tarim basins, forming a unique “three mountains surrounding two basins” landscape [22]. The climate is characterized as a typical temperate continental climate, dry with low rainfall. The average annual precipitation is 145 mm, with northern Xinjiang receiving up to 100–200 mm due to the influence of westerly circulation and Arctic Ocean moisture [23]. The region experiences large annual temperature variations and abundant sunshine. Natural vegetation is sparse, primarily consisting of grassland and desert vegetation [24].

Note: The base map was produced using the standard map from the National Geographic Information Public Service Platform, with review number GS(2024)0650, and no modifications were made to the boundary. The same applies below.

[Figure 1: see original paper]

2.2 Data Sources

2.2.1 Land Use and Simulation Data Land use data were obtained from the annual land use dataset of China produced by Wuhan University [25], which was reclassified into six land use types (cropland, forestland, grassland, water bodies, construction land, and unused land) according to Xinjiang’ s actual conditions and land classification standards. Other simulation data primarily include socioeconomic factors, distance factors, and natural factors. Detailed information is provided in Table 1. To ensure data accuracy, all data were resampled to 30 m$×$30 m resolution, with the geographic coordinate system set as GCS_{{{WGS}}_{{1984}}}.

2.2.2 Carbon Density Data Carbon density data were primarily sourced from the National Ecological Data Center Resource Sharing Service Platform (http://www.nesdc.org.cn), supplemented by carbon density data from neighboring regions [26-27]. Previous studies have shown that carbon density is influenced by regional climate and soil factors, so a correction method proposed by predecessors was adopted to obtain localized carbon density data for Xinjiang (Table 2) [28]. The specific correction formulas are:

$$Ca = 3.3968 \times Xa + 3996.1$$

$$Cb = 6.798 \times e^{0.0054 \times Xb}$$

$$Cc = 28 \times Xc + 398$$

where Ca and Cb represent soil and biomass carbon densities corrected by average annual precipitation ($\mathrm{t \cdot hm^{-2}}$); Cc represents biomass carbon density corrected by average annual temperature ($\mathrm{t \cdot hm^{-2}}$); Xa and Xb represent average annual precipitation (mm) and average annual temperature (°C), respectively.

The correction coefficients are calculated as:

$$Ka = C'a/C''a$$

$$Kb = C'b/C''b$$

$$Kc = C'c/C''c$$

$$Kd = C'd/C''d$$

where Ka and Kb are precipitation and temperature correction coefficients for biomass carbon density; Kc and Kd are correction coefficients for biomass and soil carbon density; C' a and C' 'a are soil carbon densities calculated using Xinjiang' s and national average annual precipitation, respectively ($\mathrm{t \cdot hm^{-2}}$); C' b and C' 'b are biomass carbon densities calculated using Xinjiang' s and national average annual precipitation ($\mathrm{t \cdot hm^{-2}}$); C'c and C''c are biomass carbon densities calculated using Xinjiang' s and national average annual temperature ($\mathrm{t \cdot hm^{-2}}$); C' d and C'' d are soil carbon densities calculated using Xinjiang' s and national average annual temperature ($\mathrm{t \cdot hm^{-2}}$).

2.3 Methods

2.3.1 Carbon Storage Calculation Method The carbon storage submodule in the InVEST model calculates the carbon storage corresponding to land use types for each pixel at different time points. This module can effectively simulate changes in ecosystem carbon storage and carbon source-sink relationships under multiple land use types and future land development scenarios [29]. The simulation employs the carbon pool substitution method by obtaining aboveground carbon density, belowground carbon density, soil carbon density, and dead organic matter carbon density for land use types, multiplying these with the corresponding land use type areas, and summing all results to obtain the total carbon storage of the study area [30]. The calculation formula is:

$$C_{total} = C_{above} + C_{below} + C_{soil} + C_{dead}$$

where C_{total}, C_{above}, C_{below}, C_{soil}, and C_{dead} represent total carbon storage, aboveground carbon storage, belowground carbon storage, soil carbon storage, and dead organic matter carbon storage for land use type n, respectively ($\mathrm{t \cdot hm^{-2}}$).

2.3.2 Multi-Scenario Prediction Method The Land Expansion Analysis Strategy (LEAS) module of the PLUS model inputs multiple driving factors (Table 1) and uses a random forest algorithm to evaluate their contribution and potential for land expansion, thereby revealing relationships between driving factors and land use changes. The PLUS module, combined with parameters such as land use demand and domain weights (Table 3), generates land use change for 2050. Using 2020 land use data as the baseline and incorporating land use transition matrices under different development scenarios (Table 4), three land use scenarios for Xinjiang in 2050 were established: natural development, ecological protection, and economic priority.

In the natural development scenario, historical land use change trends continue for predicting future land use. The ecological protection scenario emphasizes strengthening forest and grassland protection and slowing economic growth, thus restricting the conversion of forestland and grassland to other land types. The economic priority scenario focuses on promoting economic growth, where construction land cannot be converted to other types, but other land types can be converted to construction land.

The Kappa coefficient was used to assess the simulation performance of the model, calculated as:

$$Kappa = \frac{p_o - p_c}{p_p - p_c}$$

where p__o, p__c, and p__p represent simulation accuracy under actual, expected, and ideal conditions, respectively. In this study, the simulation accuracy Kappa > 0.75, indicating that the simulation results meet research requirements.

3 Results and Analysis

3.1 Land Use Change Characteristics in Xinjiang from 1990-2050

Due to differences in topography and climate conditions, Xinjiang' s land use distribution exhibits obvious spatial heterogeneity. From 1990 to 2020, cropland was mainly distributed around the Tarim Basin, the northern slope of the Tianshan Mountains, and the oasis zones in the southern Junggar Basin. Forestland distribution was relatively scattered, primarily in scattered areas of the Altai and Tianshan mountains in northern Xinjiang. Grassland was mainly distributed in the northern Altai Mountains, western Junggar Basin, and throughout the Tianshan region. Water bodies were primarily distributed in the Kunlun Mountains in southern Xinjiang and western Tianshan region, mainly consisting of glacier meltwater. Construction land was mainly distributed in and around urban areas. Unused land was primarily distributed in the Junggar Basin, Tarim Basin, and higher altitude areas of the Kunlun Mountains in southern Xinjiang.

From 1990 to 2020, Xinjiang' s land use types underwent significant changes (Figure 3). Unused land proportion slightly decreased from 68.65% to 67.51%, with most converting to grassland, cropland, construction land, and water bodies, with transferred areas of 47,312 km^2, 12,760 km^2, 1,557 km^2, and 7,626 km^2, respectively. Grassland and cropland also showed annual changes, with grassland decreasing and mainly converting to cropland and unused land, transferring 26,242 km^2 and 8,629 km^2, respectively. Cropland increased annually, mainly converted from grassland and unused land, with transferred-in areas of 26,242 km^2 and 12,760 km^2, respectively. Overall, unused land is the main land use type in Xinjiang, with grassland and cropland changes also being significant.

Under the three scenarios for 2020-2050, Xinjiang's land use changes show different characteristics (Figure 4). Under the natural development scenario, unused land and grassland account for 67.80% and 21.39%, respectively. Unused land continues converting to grassland, cropland, and water bodies, with transferred-out areas of 2,898 km^2, 3,963 km^2, and 3,903 km^2, respectively. Grassland area continues decreasing, converting 11,026 km^2, 5,258 km^2, and 1,557 km^2 to cropland, forestland, and unused land, respectively. Under the ecological protection scenario, cropland, water bodies, and construction land areas decrease, while forestland and grassland areas increase, with grassland accounting for 23.44% of the area. Grassland increase mainly comes from unused land and cropland conversion, with transferred-in areas of 28,346 km^2 and 4,600 km^2, respectively. Under the economic priority scenario, construction land area increases significantly by 21,969 km^2, mainly converted from grassland and cropland, with transferred-in areas of 19,969 km^2 and 1,998 km^2, respectively.

[Figure 2: see original paper] [Figure 3: see original paper] [Figure 4: see original paper]

3.2 Carbon Storage Changes in Xinjiang from 1990-2050

The changing pattern of carbon storage in Xinjiang from 1990 to 2020 shows that 90.37% of the region' s carbon storage remained relatively stable, indicating that most land use was less disturbed by human activities. Carbon storage increased in over 4.81% of the region, suggesting that land use changes in these areas enhanced carbon sequestration capacity, converting them to carbon sinks. Carbon storage decreased in 4.49% of the region, indicating weakened carbon sequestration capacity in these areas, making them carbon sources. Overall, increased and decreased carbon storage areas are basically balanced, with significant increases in carbon storage in the northern Tianshan region and oasis areas along the northern edge of the Tarim Basin, while other areas show decreasing trends.

For the 2050 projections, carbon storage changes differ among land use types under the three development scenarios. Under the natural development scenario, carbon storage in grassland and water bodies decreases by 221.61 t and 0.19 t, respectively, while carbon storage in unused land, cropland, forestland, and construction land increases by 64.41 t, 56.48 t, 1.14 t, and 0.57 t, respectively. Compared with the natural development scenario, the ecological protection scenario shows increased carbon sink area and decreased carbon source area, with relatively stable balanced area. Under the ecological protection scenario, carbon storage in grassland and forestland increases by 175.69 t and 48.39 t, respectively, while construction land and water bodies decrease by 9.33 t and 0.51 t, respectively. Under the economic priority scenario, carbon storage in construction land increases significantly by 2.86 t, while other types show minimal changes. Overall, grassland remains Xinjiang’ s most important carbon pool, and its carbon storage changes directly affect Xinjiang’ s carbon balance.

[Figure 5: see original paper]

3.3 Impacts of Land Use Change on Carbon Storage

Different land use types contribute differently to carbon storage, with grassland being the primary land type for total carbon storage in Xinjiang, followed by unused land (Table 5). From 1990 to 2020, grassland area reduction led to significant carbon storage decline, with a total loss of 224.16 t. Although forestland area is relatively small, its carbon storage proportion in total carbon storage has increased from 3.15% to 5.36%. Cropland carbon storage shows a yearly increasing trend, accounting for approximately 4.87% of total carbon storage. Meanwhile, unused land area reduction also caused carbon storage decline of 33.21 t.

Specific land use conversions have varying impacts on carbon storage. Grassland conversion to forestland increased carbon storage by 2.57×10^{6} t, while conversions to water bodies, construction land, and unused land decreased carbon storage by 7.47×10^{6} t, 2.08×10^{6} t, and 1.51×10^{6} t, respectively. Unused land conversion to cropland and grassland increased carbon storage by 2.96×10^{6} t and 8.92×10^{6} t, respectively. Overall, grassland degradation is the main cause of carbon storage loss.

Under the 2020–2050 natural development scenario, grassland conversion to unused land causes carbon storage loss of 3.53×10^{6} t, while grassland conversion to forestland increases carbon storage by 1.24×10^{6} t. Unused land conversion to grassland and cropland increases carbon storage by 1.10×10^{6} t and 3.22×10^{6} t, respectively. Overall, the ecological protection scenario increases carbon storage by 2.73×10^{6} t, with unused land conversion to grassland and cropland increasing carbon storage by 2.42×10^{6} t and 1.98×10^{6} t, respectively. Water body conversion to grassland and unused land increases carbon storage by 1.10×10^{6} t and 1.48×10^{6} t, respectively, while construction land conversion to cropland and grassland increases carbon storage by 1.99×10^{6} t and 3.39×10^{6} t, respectively, significantly enhancing regional carbon storage capacity. Under the economic priority scenario, mutual conversion between grassland and unused land basically achieves carbon storage balance. Cropland and grassland conversion to construction land causes carbon storage losses of 3.52×10^{6} t and 3.27×10^{6} t, respectively, with total carbon loss of approximately

2.31$\times10^{6}$ t.

[Figure 6: see original paper]

4 Discussion

4.1 Grassland Degradation as the Primary Cause of Carbon Storage Loss in Xinjiang

This study demonstrates that grassland area in Xinjiang has decreased annually, resulting in cumulative carbon storage loss of 224.16 t. As the second largest carbon pool in terrestrial ecosystems, grassland degradation directly weakens Xinjiang’ s carbon storage capacity. Yang et al. [31] also confirmed that grassland degradation to unused land is the main reason for carbon storage decline in Xinjiang. This conclusion is further validated in studies of the northern Tianshan slope [32] and the Tarim River Basin [14].

Factors influencing grassland degradation can be divided into natural and anthropogenic categories. In terms of natural factors, against the background of global warming, frequent extreme weather events, particularly rising temperatures, have led to drought stress that inhibits grassland vegetation growth [33]. Biological invasions, including harmful animals, plants, and microorganisms, can also cause grassland degradation [34]. Regarding anthropogenic factors, overgrazing and mowing alter grassland structure and nutrient cycling, leading to simplified grassland species composition. Additionally, excessive reclamation and lagging grassland management accelerate grassland degradation trends.

The implementation of ecological protection measures has effectively mitigated this phenomenon. For example, the Inner Mongolia section of the Yellow River Basin [24] and the forest-farmland ecotone of the Greater Khingan Mountains [35] have significantly increased carbon storage through grassland restoration and forestland protection. In recent years, Xinjiang has implemented projects such as the Three-North Shelter Forest, returning farmland to forest and grassland, and saline meadow restoration, which have initially curbed the expansion of grassland degradation area and provided possibilities for future carbon storage stability.

4.2 Impacts of Other Land Use Changes on Xinjiang’s Carbon Storage

Changes in other land use types also significantly impact Xinjiang’ s carbon storage, with differentiated mechanisms. As Xinjiang’ s third-largest carbon pool, cropland showed a continuous increase in carbon storage during 1990–2020. This phenomenon is closely related to the implementation of Xinjiang’ s “14th Five-Year Plan for Land Resource Protection and Development Utilization,” which curbs the “non-agriculturalization” and “non-grainization” of cropland, achieving coordinated growth in carbon storage while ensuring food security. However, the ecological cost of cropland expansion cannot be ignored, requiring scientific assessment of its long-term carbon sink potential while strictly adhering to cropland protection red lines.

From the perspective of carbon loss effects from construction land, rapid urbanization has brought pressure on land use transformation. In the past 20 years, Xinjiang's urbanization rate increase has led to surging demand for construction land, directly causing carbon storage reduction [36]. Moreover, urban expansion not only occupies original carbon sink land types but also generates additional carbon emissions through energy consumption and industrial activities, creating a dual carbon storage loss pattern of "spatial occupation + consumption."

Regarding the carbon sink effects of unused land, Xinjiang' s unused land is mainly desert, which makes important contributions to carbon storage [37]. Previous studies have shown that the Gurbantunggut Desert [38] and Taklimakan Desert [39] exhibit obvious carbon sink phenomena. Therefore, under Xinjiang' s special geographical conditions, scientific ecological engineering measures are expected to transform traditionally recognized "carbon-neutral" unused land into important carbon sink areas.

4.3 Limitations and Future Prospects

This study has certain limitations. Carbon density data rely on existing measured data and literature, neglecting regional differences and making it difficult to widely apply to different areas. Additionally, due to climatic conditions and geographical environment factors in Xinjiang, long-term carbon density data monitoring is scarce, limiting the accuracy of spatiotemporal dynamic change analysis of carbon storage. Carbon density changes over time, and future research should establish a local carbon density database for different ecological zones and land use types, regularly updating and monitoring carbon density changes to capture the relationship between carbon density and time, thereby improving carbon storage simulation accuracy.

Furthermore, as the "warming and humidification" trend intensifies in Northwest China, land use change patterns are altering, which inevitably increases uncertainty in land use change predictions. Therefore, parameter settings in the PLUS model need to be optimized to improve the accuracy of future land use predictions.

5 Conclusions

This study integrates the PLUS-InVEST model to comprehensively assess the spatiotemporal changes in land use and carbon storage in Xinjiang from 1990 to 2020, and quantitatively evaluates the impacts of land use change on carbon storage under different scenarios for 2050. The main conclusions are as follows:

(1) From 1990 to 2020, Xinjiang' s land use types were dominated by unused land and grassland, but their areas showed a decreasing trend annually, while other land types increased year by year.

(2) Grassland is the most important carbon pool in Xinjiang, followed by unused land. Grassland degradation is the main cause of carbon storage reduction in Xinjiang, with grassland degradation causing carbon storage loss of 224.16 t.

(3) The ecological protection scenario for 2050 contributes to energy conservation and emission reduction, with carbon storage projected to increase by 6.19$×10^{7}$ t. Under the economic priority scenario, urban construction land expansion leads to carbon storage loss of approximately 3.52$×10^{7}$ t.

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