Spatiotemporal Evolution of Carbon Storage in the Tianshan Mountains of Xinjiang Based on the InVEST Model (Postprint)

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Abstract

Investigating the impact mechanism of land use change on the spatiotemporal variation of carbon storage in the Tianshan Mountains is of great significance for the protection of arid mountain ecosystems and sustainable regional economic and social development. Based on land use data for the Xinjiang Tianshan Mountains from 1990 to 2020, and utilizing the carbon storage module of the InVEST model, this study estimated the carbon storage and its spatial distribution pattern in the Xinjiang Tianshan Mountains from 1990 to 2020, and analyzed the impact of land use change on carbon storage. The results show that: (1) The land use types in the Xinjiang Tianshan Mountains are dominated by grassland and unused land, followed by permanent glaciers and snow cover, and forest land, with smaller areas of shrubland, water bodies, construction land, and wetlands. (2) From 1990 to 2020, the carbon storage in the Xinjiang Tianshan Mountains showed a continuous increasing trend overall, with a total increase of 19.49 Tg, and grassland, unused land, and forest land contributed the most to the total carbon storage. (3) The spatial distribution pattern of carbon storage over the past 30 years has been relatively stable, with nearly 88% of the region showing no significant change, and its spatial distribution pattern is closely related to the distribution of vertical natural zones. (4) The conversion among three land use types—grassland, permanent glaciers and snow cover, and unused land—is the main contributor to the spatiotemporal evolution of carbon storage in the Xinjiang Tianshan Mountains. This study can provide scientific support for carbon balance management in arid mountain ecosystems and the formulation of policies for emission reduction and carbon sink enhancement, and is of great significance for building the Green Silk Road and constructing a China-Central Asia community with a shared future.

Full Text

Preamble

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Research on Spatiotemporal Evolution of Carbon Storage in the Xinjiang Tianshan Mountains Based on the InVEST Model

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Abstract: Investigating the impact mechanisms of land use change on spatiotemporal carbon storage dynamics in the Tianshan Mountains is crucial for protecting mountain ecosystems and ensuring sustainable regional economic and social development in arid zones. Based on land use data for the Xinjiang Tianshan Mountains from 1990 to 2020, this study estimated carbon storage and its spatial distribution patterns using the InVEST model carbon storage module, and analyzed the influence of land use change on carbon storage. The results showed that: (1) Grassland and unused land were the dominant land use types, followed by permanent glaciers and snow cover, and forest land, with minimal areas of shrubland, water bodies, construction land, and wetlands. (2) Carbon storage exhibited a continuous increasing trend, with a total increase of 19.49 Tg. Grassland, unused land, and forest land contributed the most to total carbon storage. (3) The spatial distribution pattern of carbon storage remained relatively stable over the past 30 years, with nearly 88% of regions showing no significant change, and this pattern was closely related to vertical natural zone distribution. (4) Conversions among three land use types—grassland, permanent glaciers and snow, and unused land—were the main contributors to spatiotemporal carbon storage evolution in the Tianshan Mountains. This study provides scientific support for carbon balance management and emission reduction policy formulation in arid zone mountain ecosystems, and is significant for building the Green Silk Road and fostering a China-Central Asia community with a shared future.

Keywords: carbon storage; ecosystem services; InVEST model; mountain

ecosystem; Xinjiang Tianshan Mountains

Introduction

Terrestrial ecosystem carbon storage plays a critical role in the global carbon cycle and climate change, and is essential for reducing atmospheric CO_2 concentrations, regulating regional microclimates, mitigating global climate change, and maintaining ecological balance [?]. Achieving carbon neutrality by 2060 has become a major long-term strategic goal for China, making research on terrestrial ecosystem carbon storage vital for maintaining global carbon emission-absorption balance [?]. With the advancement of the Silk Road Economic Belt, the arid zone mountains of Central Asia have become increasingly important as ecological barriers for building a China-Central Asia community with a shared future. These mountains are hotspots of landscape diversity and biodiversity, yet also ecologically fragile and environmentally sensitive areas.

Research on terrestrial ecosystem carbon storage has primarily focused on three aspects: (1) Carbon storage estimation studies, with assessment scales expanding from single ecosystem types such as forests [?], grasslands [?], and wetlands [?] to broader spatial scales including watersheds [?], typical ecological regions [?], national [?], and global levels [?]. (2) Carbon storage estimation methodology, evolving from traditional plot survey methods to current approaches combining remote sensing monitoring with models. Among these, the InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) model carbon storage module has been widely applied for ecosystem carbon storage estimation due to its relatively simple operation, flexible parameter adjustment, and dynamic spatial visualization capabilities [?, ?]. (3) Spatiotemporal evolution mechanisms and influencing factors of carbon storage, particularly the impact of regional land use change on ecosystem carbon storage [?].

China' s arid zone mountains are mainly distributed in the inland northwest regions with scarce precipitation. Glaciers, snow cover, lakes, wetlands, forests, grasslands, and deserts constitute important spatial carriers of the national "Two Barriers and Three Belts" ecological pattern, providing numerous ecosystem services including water conservation, carbon sequestration, soil erosion prevention, disaster protection, food and timber provision, cultural preservation, and biodiversity maintenance. These mountains play an irreplaceable role in maintaining national ecological security and promoting high-quality development in northern China.

The Xinjiang Tianshan Mountains represent the most typical example of large-scale mountain ecosystems in the world' s temperate arid zones and are highly sensitive to global change, with extremely fragile ecological environments [?]. The region is rich in natural resources and energy, holding important status in the ecological and geographical pattern of Central Asian arid zones and serving as a critical natural barrier affecting weather, climate, and ecological environments in Xinjiang and even central-western China [?]. The main vegetation types include steppe, forest, shrubland, cropland, and desert, with a complete vertical natural zonation from warm temperate desert to snow and ice zones [?]. The Tianshan range spans Xinjiang, forming a natural geographical boundary between the Junggar and Tarim Basins, and is sandwiched between the Taklamakan and Gurbantunggut Deserts, creating a globally typical mountain-oasis-desert ecosystem [?]. This unique ecosystem makes it one of the world' s biodiversity hotspots [?].

Strengthening research on the spatiotemporal patterns of ecosystem carbon storage in the Xinjiang Tianshan Mountains can enrich studies on mountain ecosystem services in arid zones and provide scientific support for sustainable development and climate change mitigation. Therefore, based on land use data and using the InVEST model carbon storage module, this study selected four periods (1990, 2000, 2010, and 2020) to analyze spatiotemporal evolution characteristics of ecosystem carbon storage and its relationship with land use patterns in the Xinjiang Tianshan Mountains. The findings are significant for scientifically formulating and implementing complex management policies for mountain ecosystem services in arid zones.

1.1 Study Area Overview

The Xinjiang Tianshan Mountains (73°50 28 ~95°33 56 E, 39°24 40 ~45°23 8 N) are located in central Xinjiang [Figure 1: see original paper]. The range extends approximately 1,852 km, comprising multiple mountain ranges, intermontane basins, and valleys [?], spanning across Kizilsu Kirghiz Autonomous Prefecture, Kashgar Prefecture, Aksu Prefecture, Ili Kazakh Autonomous Prefecture, Bortala Mongol Autonomous Prefecture, Tacheng Prefecture, Bayingolin Mongol Autonomous Prefecture, Changji Hui Autonomous Prefecture, Urumqi City, Turpan City, and Hami City, covering an area of about 23.53$\times10^{4}$ km^2 (14.13% of Xinjiang' s total area). The average ridge line elevation is 4,000 m, with the highest peak (Tomur) reaching 7,443 m. The region has a typical temperate continental climate with significant temperature differences between north and south slopes. The north slope has an average annual temperature of 2.5~5.0°C, while the south slope averages 7.5~10.0°C. The multi-year average annual precipitation is 987$\times10^{8}$ m^3 [?]. Known as the "Water Tower of Central Asia," the Tianshan Mountains are the source of many Central Asian rivers and one of the regions most sensitive to climate change [?]. The mountain forest belt plays important roles in water and soil conservation, water source 涵养, and carbon sequestration [?], and is crucial for maintaining oasis agriculture and urban development on both sides of the Tianshan range.

1.2 Data Sources

Land use data were obtained from Zenodo (https://doi.org/10.5281/zenodo.4417810) with a spatial resolution of 30 m, meeting research requirements. The data include nine land use types: cropland, forest land, shrubland, grassland, water bodies, permanent glaciers and snow, unused land, construction land, and wetlands. The data were clipped to generate land use maps for the Xinjiang Tianshan Mountains. Temperature and precipitation data were sourced from the National Tibetan Plateau Data Center (http://data.tpdc.ac.cn/en/data/0b887b5f-3098-4213-9b57-7c68b6c3d7f3/) with a resolution of 1 km.

1.3.1 Carbon Storage Assessment Based on the InVEST Model

Carbon storage in ecosystems includes four basic carbon pools: aboveground biomass, belowground biomass, soil carbon, and dead organic matter. Total carbon storage is calculated by multiplying the area of each land use type by its average carbon density and summing across all types:

$$C_{\text{total}} = \sum_{i=1}^{n} (C_{i,\text{above}} + C_{i,\text{below}} + C_{i,\text{soil}} + C_{i,\text{dead}}) \times A_i$$

where $C_{i,\text{above}}$, $C_{i,\text{below}}$, $C_{i,\text{soil}}$, and $C_{i,\text{dead}}$ are the aboveground, belowground, soil, and dead organic matter carbon densities ($\text{t} \cdot \text{hm}^{-2}$) for land use type i; A_i is the area (hm^2) of land use type i; C_{total} is total ecosystem carbon storage (Tg); and n is the number of land use types (n=9 in this study).

1.3.2 Carbon Density Values and Correction for Different Land Use Types

Initial carbon density data for different land use types were obtained from existing literature [?], prioritizing: (1) local Xinjiang field measurements, (2) studies from northwest arid and semi-arid regions, and (3) national-scale data. Since these data may contain errors relative to actual measurements, we applied climate-based corrections. Research shows that biomass and soil organic carbon densities are positively correlated with precipitation and negatively correlated with temperature [?], a method widely applied in arid zones [?]. Temperature and precipitation data were used to correct initial carbon densities to obtain localized values.

The correction formulas are:

Precipitation-based regression models (MAT ≤ 10°C):

$$SP = 79.1 + 0.07 \times MAP$$

$$BP = 14.4 + 0.03 \times MAP$$

Temperature-based regression models (MAP ≤ 400 mm):

$$ST = 100.5 - 5.8 \times MAT$$

$$BT = 16.7 - 1.3 \times MAT$$

For MAT > 10°C and MAP > 400 mm:

$$ST = 157.7 - 3.4 \times MAT$$

$$BT = 43.0 - 0.4 \times MAT$$

where SP and BP are soil and biomass carbon densities ($\mathrm{t} \cdot \mathrm{hm}^{-2}$) considering precipitation; ST and BT are soil and biomass carbon densities ($\mathrm{t} \cdot \mathrm{hm}^{-2}$) considering temperature; MAT and MAP are mean annual temperature (°C) and precipitation (mm).

Correction coefficients were calculated as:

$$K_{\text{biomass}} = \text{Average}(C'_{\text{biomass,precip}}, C'_{\text{biomass,temp}})$$

$$K_{\text{soil}} = \text{Average}(C'_{\text{soil,precip}}, C'_{\text{soil,temp}})$$

where K_{biomass} and K_{soil} are correction coefficients; C' values represent carbon densities at Tianshan and national scales. The final corrected carbon densities for Xinjiang Tianshan land use types are shown in Table 1 and Table 2 .

2.1 Land Use Change Characteristics in the Tianshan Mountains

From 1990 to 2020, grassland dominated the study area, covering approximately 79.31% of the total area and widely distributed on both north and south slopes. Unused land was the second major type (>10% of total area), mainly distributed in the transition zone between the Tianshan Mountains and Tarim Basin where climate is arid and vegetation sparse. Permanent glaciers and snow cover and forest land each accounted for about 5% of the area, with glaciers/snow concentrated above the snow line in high-altitude regions (e.g., Kharkhira, Irenhabirga, Bogda mountains), and forests distributed in the mid-mountain forest belt of the north slope and river valleys of the south slope. Cropland, water bodies, wetlands, shrubland, and construction land each covered less than 5% of the total area.

Land use dynamics from 1990 to 2020 showed increases in construction land, forest land, cropland, water bodies, and wetlands. Unused land increased the most (6,961.22 km^2), followed by forest land (5,452.89 km^2). Cropland expanded rapidly (1,056.71 km^2). Grassland and permanent glacier/snow areas decreased by 13,017.22 km^2 and 1,150.34 km^2, respectively. Xinjiang' s climate has shown overall warming and wetting trends [?], causing glacier retreat and increases in water body and wetland areas. Major ecological projects (e.g., Grain for Green, Natural Forest Protection, Three-North Shelterbelt) have effectively protected and restored forest resources. However, overgrazing remains a primary cause of grassland degradation [?].

2.2 Spatiotemporal Characteristics of Carbon Storage in the Tianshan Mountains

Using the InVEST model, total carbon storage in the Xinjiang Tianshan Mountains was estimated as 1,604.47 Tg, 1,605.45 Tg, 1,606.66 Tg, and 1,623.96 Tg for 1990, 2000, 2010, and 2020, respectively, with average carbon densities of 67.49 $t \cdot hm^{-2}$, 68.23 $t \cdot hm^{-2}$, 68.27 $t \cdot hm^{-2}$, and 68.32 $t \cdot hm^{-2}$. Carbon storage showed a continuous increasing trend over the 30-year period, with a total increase of 19.49 Tg and an average annual growth rate of 0.65 Tg (1.23%). The fastest increase occurred during 2010-2020 (9.30 Tg), primarily due to significant forest area expansion, accounting for 88.76% of the total increase. Carbon storage increased slowly during 1990-2000 and 2000-2010, with increments of 0.98 Tg and 1.21 Tg, respectively.

Spatially, the carbon storage distribution pattern changed little over the 30 years [Figure 3: see original paper]. High-value areas were mainly distributed in the mountain steppe belt, mid-mountain forest belt, subalpine meadow belt, alpine meadow belt, river valleys, and intermontane basins with good vegetation cover and strong carbon sequestration capacity. Low-value areas were primarily in the piedmont desert belt, alpine cushion vegetation belt, and snow-ice belt. The spatial pattern was closely related to vertical natural vegetation zonation —high-value areas dominated by forest and high-coverage grassland, low-value areas by desert steppe and alpine cushion vegetation.

To clarify spatial changes, raster subtraction was performed on carbon storage distribution maps for different periods. Following Liu et al. [**?**], areas with change values >1.23% were classified as carbon gain zones, <-1.23% as carbon loss zones, and between -1.23% and 1.23% as stable zones [Figure 4: see original paper]. Results showed that 88.76% of the region remained stable, indicating minimal land use change and human disturbance. Carbon loss zones decreased from 4.37% to 3.61%, while gain zones increased from 3.79% to 4.01%. Overall, carbon storage remained relatively stable, with gain and loss zones roughly balanced. Notable increases occurred in the Ili Valley and Bayinbuluk Wetland areas, while most of the western Tianshan showed decreasing trends.

2.3 Impact of Land Use Change on Carbon Storage

Land use type conversions significantly affect carbon storage changes [Figure 5: see original paper]. From 1990 to 2020, the contributions to total carbon storage were: grassland > unused land > forest land > cropland > wetland > water body > shrubland > construction land > permanent glaciers and snow. Grassland, unused land, and forest land were the main carbon pools.

Temporal changes in carbon storage by land use type showed that from 1990 to 2020, carbon storage in cropland, forest land, unused land, and wetland increased significantly, with forest land showing the largest increase (81.96 Tg). Grassland carbon storage decreased substantially (27.75 Tg). Shrubland, water bodies, permanent glaciers/snow, and construction land showed minimal changes.

Analyzing land use conversions: From 1990-2020, 转出 of permanent glaciers/snow contributed the largest carbon storage increase (16.45 Tg), mainly converting to unused land, grassland, and forest land, increasing carbon storage by 7.01 Tg, 3.40 Tg, and 4.12 Tg, respectively. Unused land conversion contributed 15.29 Tg, primarily through conversion to grassland (25.43 Tg increase), but also to permanent glaciers/snow (11.88 Tg decrease). Water body and shrubland conversions increased carbon storage by 1.21 Tg and 0.54 Tg, respectively. Grassland conversion caused the largest carbon loss (46.94 Tg), despite some conversion to forest land increasing storage by 22.16 Tg, conversions to unused land, permanent glaciers/snow, and water bodies decreased storage by 36.79 Tg, 7.01 Tg, and 0.14 Tg, respectively. Wetland, cropland, and forest land conversions caused minor decreases (0.07 Tg, 0.004 Tg, and 0.004 Tg, respectively).

From the perspective of land use type 转入, forest land 转入 contributed the largest carbon storage increase (22.16 Tg), mainly from grassland conversion. Grassland 转入 increased storage by 25.43 Tg, primarily from unused land conversion. Wetland 转入 increased storage by 4.12 Tg, mainly from grassland and cropland conversion. Cropland 转入 increased storage by 0.54 Tg, mainly from grassland and unused land conversion. Unused land 转入 was the primary factor for carbon storage loss (11.88 Tg), followed by permanent glaciers/snow 转入 (7.01 Tg), mainly from unused land and grassland conversion.

Across different periods, conversions of permanent glaciers/snow and unused land (转出), and grassland and forest land (转入) were the main contributors to carbon storage enhancement. Carbon storage increases were mainly due to grassland converting to forest land and wetland, unused land converting to grassland, and permanent glaciers/snow converting to unused land, which improved vegetation cover and biomass. Carbon storage decreases were mainly caused by grassland conversion to unused land, permanent glaciers/snow, and water bodies, as well as unused land conversion to glaciers/snow. The persistent trend of carbon loss from grassland conversion reflects unresolved overgrazing issues in mountainous areas. The fluctuating trend of carbon gain from permanent glaciers/snow and unused land conversion reflects changing conversion areas between these types over time.

3.1 Applicability Analysis of Carbon Density

The InVEST model was used to estimate terrestrial ecosystem carbon storage, with climate variables applied to localize carbon density parameters—a method widely used and validated in regional carbon storage assessments [?]. To ensure applicability and accuracy of corrected carbon densities in the Xinjiang Tianshan region, validation against measured data or related studies was necessary.

Xu et al. [?] integrated experimental and literature data, finding that measured aboveground, belowground, and soil carbon densities for grassland in the Xinjiang Tianshan region ranged 0.14-1.99 $t \cdot hm^{-2}$, 0.68-7.09 $t \cdot hm^{-2}$, and 24-253.5 $t \cdot hm^{-2}$, with means of 0.73 $t \cdot hm^{-2}$, 3.70 $t \cdot hm^{-2}$, and 126.69 $t \cdot hm^{-2}$, respectively. The corrected grassland carbon densities fell within these measured ranges, with aboveground and belowground values close to measured means. The corrected soil carbon density showed a larger relative error (40.37%) compared to the measured mean, likely because sampling points had high vegetation coverage (>60%) and were dominated by high-coverage grassland types, with fewer samples from medium- and low-coverage grasslands.

Zhang et al. [?] estimated soil carbon densities for western China' s arid zone based on first and second soil survey data, reporting average values of 158.8 $t \cdot hm^{-2}$ for oasis cropland, 204.2 $t \cdot hm^{-2}$ for forest, 123.6 $t \cdot hm^{-2}$ for shrubland, 77.1 $t \cdot hm^{-2}$ for meadow steppe, 63.9 $t \cdot hm^{-2}$ for desert steppe, and 79.5 $t \cdot hm^{-2}$ for wetland. Compared with our corrected soil carbon densities, forest and grassland showed larger differences (relative errors of 32.10% and 19.42%, respectively), while other land use types were relatively similar. Overall, our results are consistent with existing measured data, indicating that the corrected carbon densities are reliable and reflect actual conditions in the study area.

The InVEST model calculates carbon storage based on land use type changes, but simplifies carbon cycling processes by ignoring factors such as photosynthetic rates and soil microbial activity, which reduces estimation accuracy [?] and introduces uncertainty. However, the model provides a feasible method for regional carbon storage estimation.

3.2 Analysis of Factors Influencing Carbon Storage Changes

This study used the InVEST model to assess the overall carbon sequestration capacity of the Xinjiang Tianshan Mountains and carbon storage changes caused by different land use type conversions. Results show that the region' s carbon sequestration capacity continued to strengthen from 1990 to 2020. This increase mainly benefited from forest restoration and glacier retreat converting to unused land, while grassland degradation to unused land was the direct cause of carbon storage loss.

The Three-North Shelterbelt Program (initiated in 1978), Grain for Green Project, and Natural Forest Protection Project have expanded forest area and improved quality, significantly increasing carbon densities of both planted and natural forests [?]. The carbon sequestration benefits of these projects have been verified in other arid and semi-arid regions such as the Weihe River Basin [?] and Shiyang River Basin [?]. Climate warming has caused glacier retreat, with primary succession on retreating surfaces gradually establishing material cycles and increasing soil carbon storage [?].

Grassland degradation in the Xinjiang Tianshan region is caused by both climate change and human activities. Although precipitation has increased during the growing season, rising temperatures have enhanced evapotranspiration, worsening drought conditions in mountainous areas [?]. Drought frequency during the growing season exceeds 50% [?], directly affecting grassland growth. Grazing is the main human disturbance, with long-term overgrazing causing carbon loss [?]. Increased grazing intensity leads to grassland degradation and declining aboveground, litter, and total carbon storage [?]. Therefore, strengthened grazing management is needed to implement livestock-forage balance, maintain appropriate stocking rates, and enhance grassland carbon sequestration capacity.

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4 Conclusions

Analysis of land use types and spatiotemporal carbon storage changes in the Xinjiang Tianshan Mountains yields the following conclusions:

1) From 1990 to 2020, grassland and unused land were the dominant land use types. Significant land use changes occurred, with rapid increases in unused land, forest land, and cropland areas, while grassland and glacier areas continued to decrease.
2) Total carbon storage in the study area was 1,604.47 Tg, 1,605.45 Tg, 1,606.66 Tg, and 1,623.96 Tg for 1990, 2000, 2010, and 2020, respectively, showing a continuous increasing trend with a total increase of 19.49 Tg. Grassland, unused land, and forest land were the primary carbon pools.
3) The spatial distribution pattern of carbon storage changed little over the 30 years and was closely related to vertical natural zone distribution. Approximately 88% of the region remained stable.
4) Conversions among grassland, permanent glaciers and snow, and unused land were the main contributors to carbon storage changes. Increases in forest and unused land areas were the primary reasons for carbon storage gains, while grassland area reduction increased carbon storage losses.

In summary, the ecosystem carbon sequestration capacity of the Xinjiang Tianshan Mountains has strengthened in recent years. Carbon storage increases mainly benefited from ecological land expansion (forest and grassland), while decreases were primarily caused by grassland degradation. Therefore, it is essential to synergistically promote major ecological projects such as Grain for Green and the Three-North Shelterbelt, stabilize and expand reforestation areas, and adopt multiple afforestation methods combining trees, shrubs, and grasses to enhance ecosystem carbon sequestration capacity. Using the National Important Ecosystem Protection and Restoration Major Project Master Plan (2021-2035) as an opportunity, integrated protection and restoration of mountains, rivers, forests, farmlands, lakes, and grasslands should be advanced. Grassland grazing bans, rest periods, rotational grazing, and livestock-forage balance should be implemented, along with grazing withdrawal and degraded grassland restoration to increase ecosystem carbon sinks. Climate change monitoring, early warning, and risk management should be strengthened to enhance the resilience of fragile ecosystems in arid zones to climate change.

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Note: Figure translations are in progress. See original paper for figures.