Impacts of Land Use Change on Carbon Storage and Economic Value Estimation in the Qilian Mountains Region: Postprint

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Abstract

Human activities are the primary driving factors of land use change, and land use/cover change indirectly affects ecosystem service values by influencing the structure and function of terrestrial ecosystems. This study analyzes the characteristics of land use change in the Qilian Mountains region from 2000 to 2020 based on the land use transfer matrix and dynamic degree, estimates the carbon storage of ecosystems in the Qilian Mountains region using the InVEST model, and calculates the economic value of carbon storage for each period using the compound interest present value formula. The results show that: (1) From 2000 to 2020, grassland and unused land were the main land use types in the Qilian Mountains region, accounting for over 80% of the total area of land use types, and the conversion between them was the most significant. Due to intensified human activities and the advancement of urbanization, the area of forest land and unused land in the Qilian Mountains region decreased, while the area of other land types increased; (2) Owing to favorable geographical conditions, enhanced vegetation conservation efforts, and artificial management, the carbon storage in the Qilian Mountains region increased by 44.26\$$\times 104 t from 2000 to 2020, exhibiting a spatial distribution pattern of "low in the northwest and high in the south$ yuan over the 20 a period, with a growth rate of 71.5%, becoming the main driving force for the increase in economic value of carbon storage in the region. The carbon storage in the Qilian Mountains region shows an increasing trend. Relevant departments should, while continuing previous management approaches, also remain vigilant regarding the impacts of climate change on carbon storage in the future. The research results can provide a scientific basis for regional formulation of optimized land use objectives, promoting sustainable development, and addressing global climate change.

Full Text

Impact of Land Use Change on Carbon Storage and Economic Value Estimation in the Qilian Mountain Region

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Abstract

Human activities are the primary drivers of land use change, and land use/cover change indirectly affects the value of ecological services by influencing the structure and function of terrestrial ecosystems. This study analyzed the characteristics of land use change in the Qilian Mountain region from 2000 to 2020 based on land use transfer matrices and dynamic degree methods, applied the InVEST model to estimate ecosystem carbon storage, and combined these results with compound present value formulas to estimate the economic value of carbon storage for each period. The results showed that grassland and unused land were the main land use types in the Qilian Mountains during 2000–2020, accounting for over 80% of the total land area, with the most significant conversion occurring between these two types. Due to intensified human activities and accelerated urbanization, forest and unused land areas decreased while other land types increased in the Qilian Mountains. Owing to the region' s suitable geographic environment, strengthened vegetation protection, and artificial management efforts, carbon storage in the Qilian Mountains increased by 44.26$\times10^{4}$ t from 2000 to 2020, exhibiting a spatial distribution pattern of "low in the northwest and high in the southeast" that was significantly correlated with land use type distribution. Specifically, carbon storage in cultivated land, grassland, and water bodies increased by 73.1$\times10^{4}$ t, while carbon storage in forest land and unused land decreased by 28.8$\times10^{4}$ t. The economic value of carbon storage in the Qilian Mountains increased from 2325.9$\times10^{6}$ yuan to 3908.8$\times10^{6}$ yuan between 2000 and 2020, representing an increment of 1582.9$\times10^{6}$ yuan and a growth rate of 68.1%. Notably, the economic value of grassland carbon storage increased by 851.8$\times10^{6}$ yuan over the 20-year period, with a growth rate of 71.5%, becoming the main driver of increased carbon storage economic value in the region. Carbon storage in the Qilian Mountains shows an increasing trend, and relevant authorities should continue previous management schemes while remaining vigilant about the impacts of current climate change on carbon storage. These research results provide a scientific basis for regional land use optimization target setting, sustainable development promotion, and global climate change response.

Keywords: land use; InVEST model; carbon storage; economic value of carbon storage; Qilian Mountains

1 Study Area and Methods

1.1 Study Area Overview

The Qilian Mountain region (93.4°-103.4°E, 35.8°-40.0°N) is located in northwestern China at the border of Gansu and Qinghai provinces (Fig. 1 [Figure 1: see original paper]), extending from Wushaoling in the east to Dangjin Pass in the west, adjacent to the Hexi Corridor in the north and the Qaidam Basin in the south. The region features a typical continental climate and represents a biodiversity hotspot and important ecological zone in China. The Qilian Mountain region has diverse soil types with obvious vertical distribution characteristics and abundant mineral and cultural resources. Therefore, ecological protection of the Qilian Mountains is crucial not only for regional ecological stability but also for the ecological balance and sustainable economic and social development of western China as a whole.

1.2 Data Sources

Land use data were obtained from the Resource and Environmental Science Data Center of the Chinese Academy of Sciences (https://www.resdc.cn/). National annual average climate data were derived from the *China Climate Bulletin*, while regional annual average temperature data for the study area came from the *China Ground Meteorological Data Standard Value Dataset* (http://data.cma.cn). Carbon density data are presented in Table 1 and were primarily obtained through two approaches: first, by calculating average values from measured data in reference literature, and second, by correcting national-scale carbon density data using correction formulas for areas where data were difficult to obtain. Due to land hardening in construction areas, the carbon density of construction land was considered to be zero in this study.

1.3 Methods

1.3.1 Land Use Transfer Matrix The land use transfer matrix is a two-dimensional matrix representing the mutual conversion of land use types within a specific time period and region, indicating land use structure and change direction:

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

where S_{ij} represents the area of land use type i converted to type j (hm^2), and n is the number of land use types.

1.3.2 Land Use Dynamic Degree Land use dynamic degree reflects the rate of land use change in a region over a certain period, including single land use dynamic degree (K) and comprehensive land use dynamic degree (LC):

$$K = \frac{U_b - U_a}{U_a} \times \frac{1}{T} \times 100\%$$

where K is the dynamic degree of a specific land use type, U_a and U_b are the areas of that land use type at the beginning and end of the study period (hm^2), respectively, and T is the study duration (years).

$$LC = \frac{\sum_{i=1}^{n} \sum_{j=1, j \neq i}^{n} |LU_{i-j}|}{2 \sum_{i=1}^{n} LU_i} \times \frac{1}{T} \times 100\%$$

where LC is the comprehensive land use dynamic degree, LU_i is the area of land use type i at the start of the study period (hm^2), and LU_{i-j} is the absolute area of land converted from type i to type j during the study period (hm^2).

1.3.3 InVEST Model This study employed the Carbon Storage and Sequestration module of the InVEST model to calculate carbon storage. Terrestrial carbon pools primarily include aboveground biomass, belowground biomass, soil, and dead organic matter. Carbon storage is obtained by multiplying the carbon density of each land use type by its corresponding area:

$$C_{total} = \sum_{k=1}^{n} C_k \times A_k$$

where C_{total} is the total regional terrestrial ecosystem carbon storage (t), C_k is the carbon density of land use type k ($t \cdot hm^{-2}$), A_k is the area of land use type k (hm^2), and n is the number of land use types. The carbon density C_k is calculated as:

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

where C_{above} is aboveground biomass carbon density ($t \cdot hm^{-2}$), C_{below} is belowground biomass carbon density ($t \cdot hm^{-2}$), C_{soil} is soil carbon density ($t \cdot hm^{-2}$), and C_{dead} is dead organic matter carbon density ($t \cdot hm^{-2}$).

1.3.4 Compound Present Value Method The compound present value method originates from commodity economics and incorporates the time value of money, serving as an important indicator for investment decision-making by individuals and enterprises. Although widely applied in economics, this method has not yet been explored for terrestrial carbon storage economic value estimation. This study obtained carbon prices from carbon trading platforms, using the average annual carbon trading price from 2000–2020 as the final carbon price value, and derived carbon trading prices for each year through the compound present value formula and conversion coefficients (Table 2). Compound present value represents the current value of a specific future amount calculated with compound interest:

$$P_n = F \times (P/F, n) = F \times \frac{1}{(1+e)^n}$$

where P_n is the carbon price in period n (yuan), F is the final carbon price value (yuan), $(P/F, n)$ is the compound present value factor, e is the discount rate, and n is the period number.

1.3.5 Carbon Storage Value Estimation Carbon storage value represents the economic value required for ecosystems to absorb and store carbon:

$$P_c = \sum_{n=1}^{n} C_n \times P_n$$

where P_c is the total economic value of terrestrial ecosystem carbon storage (yuan), C_n is the carbon storage in period n (t), and P_n is the carbon trading price in period n (yuan $\cdot$ t^{-1}).

2 Results

2.1 Spatiotemporal Analysis of Land Use Change

Based on land use area data for the Qilian Mountain region, we obtained land use transfer matrices and dynamic degree changes for 2000–2020 (Fig. 2 [Figure 2: see original paper]). The Qilian Mountain region is dominated by grassland and unused land, which together account for over 80% of the total area, with frequent conversion among various land use types. Grassland showed the most significant area increase, growing by 3605.2 hm^2 (17.8%) over the past 20 years. The first decade saw an increase of 3347.5 hm^2, while the second decade added 257.7 hm^2. Water bodies, cultivated land, and construction land also increased during this period, with expansions of 1386.4 hm^2 (32.4%), 136.1 hm^2 (17.8%), and 241.2 hm^2 (40.7%), respectively. Conversely, forest land and unused land showed decreasing trends, with unused land experiencing the most significant reduction of 4734.7 hm^2 (21.7%), including a 335.8 hm^2 decrease in the first decade and a 40.7 hm^2 decrease in the second decade. Forest land decreased by 40.7 hm^2, representing the smallest decline at 0.02%.

The single land use dynamic degree analysis (Fig. 3 [Figure 3: see original paper]) revealed that construction land had the largest absolute dynamic degree value at 3.24%, followed by water bodies, unused land, and cultivated land. Forest land showed the smallest absolute dynamic degree value at only 0.01%.

From a comprehensive land use dynamic perspective, the Qilian Mountain region exhibited fluctuating changes in land use dynamic degree during 2000-2020, decreasing from 0.25% to 0.03% and then rising to 0.28%, with an overall increasing trend.

The spatial distribution of land use types in the Qilian Mountain region presented distinct patterns (Fig. 3 [Figure 3: see original paper]). Cultivated land accounted for approximately 2.98% of the total area, primarily distributed in the northeastern and southeastern regions, with change areas mainly concentrated in the southeast. Grassland, comprising 51.9% of the area, was mainly distributed in the northern, southern, and southeastern regions, with change areas primarily located in the northern and central southeastern zones. Forest land, representing 19.9% of the area, showed slight decreases and was mainly distributed in the southeast, with change areas scattered throughout the study region. Water bodies were primarily located in the southern and northwestern central areas, with change areas scattered in the northwest and partially concentrated in the middle northeastern section. By 2020, construction land area had increased, with growth mainly distributed in the northern and central sections of the study area and scattered across the western and southeastern regions.

2.2 Spatiotemporal Analysis of Carbon Storage

Temporal changes in carbon storage for various land use types in the Qilian Mountain region (Fig. 4 [Figure 4: see original paper]) indicate that total carbon storage showed a fluctuating increasing trend from 2000 to 2020, rising from 22.6$\times10^{4}$ t to 22.2$\times10^{4}$ t. Notably, total carbon storage experienced a slight decline during 2010-2015. Carbon storage in cultivated land, grassland, and water bodies increased, while carbon storage in forest land and unused land decreased. Specifically, cultivated land carbon storage showed an increasing-decreasing-increasing pattern, rising overall by 29.4$\times10^{4}$ t, with a 1.4$\times10^{4}$ t decrease during 2010-2015. Forest land carbon storage exhibited a decreasing-increasing-decreasing trend, with an overall decline of 11$\times10^{4}$ t. Grassland carbon storage showed a decreasing-increasing pattern, increasing by 236.1$\times10^{4}$ t overall, with a 97.0$\times10^{4}$ t decrease during 2000-2005 and a 39.6$\times10^{4}$ t increase during 2005-2010. Water body carbon storage displayed an increasing-decreasing-increasing trend, with an overall increase of 22.2$\times10^{4}$ t, including decreases of 9.9$\times10^{4}$ t and 7.8$\times10^{4}$ t during 2000-2005 and 2010-2015, respectively. Unused land carbon storage showed a continuous decreasing trend, with an overall reduction of 227.1$\times10^{4}$ t.

The spatial distribution of carbon storage in the Qilian Mountain region (Fig. 5 [Figure 5: see original paper]) remained largely consistent across different periods, generally presenting a "low in the northwest and high in the southeast" pattern. High carbon storage areas were primarily distributed in the eastern and central regions, dominated by forest land and grassland. Medium carbon storage areas were scattered in the western region, mainly comprising grassland

and water bodies. Low carbon storage areas were predominantly located in the western and central regions, primarily consisting of unused land. During 2000-2020, carbon storage increase areas in the Qilian Mountain region were mainly distributed in the central zone, while carbon storage decrease areas were sporadically distributed throughout the entire region.

2.3 Changes in Carbon Storage Economic Value

The economic value of carbon storage in the Qilian Mountain region increased from 2325.9×10^{6} yuan to 3908.8×10^{6} yuan during 2000-2020, representing an increment of 1582.9×10^{6} yuan and a growth rate of 68.1% (Table 4). Cultivated land carbon storage economic value showed an increasing-decreasing-increasing trend, with an overall increase of 302.3×10^{6} yuan (21.7% growth rate). Forest land and grassland carbon storage economic values increased by 246.3×10^{6} yuan (53.9% growth rate) and 851.8×10^{6} yuan (71.5% growth rate), respectively. In contrast, cultivated land carbon storage economic value accounted for the smallest proportion, with an average annual proportion of only 18.6%. Water body carbon storage economic value increased by 131.3×10^{6} yuan, with the highest growth rates of 22.2% and 21.9% during 2005-2010 and 2015-2020, respectively. Unused land carbon storage economic value decreased by 51.2×10^{6} yuan, with the largest decline of 23.8% during 2000-2005.

According to the proportion of carbon storage economic value by land use type (Fig. 6 [Figure 6: see original paper]), grassland, forest land, and unused land accounted for the highest proportions, with average proportions of 51.9%, 19.9%, and 18.6%, respectively. Cultivated land had the smallest proportion, with an average annual proportion of only 2.98%. Grassland carbon storage economic value was the largest, while cultivated land carbon storage economic value was the smallest, and the increase in grassland carbon storage economic value was the main driver of increased carbon economic value in the Qilian Mountain region.

3 Discussion

3.1 Carbon Storage Response to Land Use Change

Land use change has long been a key factor affecting carbon storage changes in terrestrial ecosystems. Whether the transformation is from forest land to cultivated land, from construction land to agricultural land, or the development and construction of unused land, these changes profoundly impact terrestrial ecosystem carbon storage and its spatiotemporal variation. This study applied the InVEST Carbon Storage and Sequestration module to analyze the spatiotemporal distribution characteristics of carbon storage for various land use types in the Qilian Mountain region. With population growth and urbanization advancement, land use patterns in the Qilian Mountain region have undergone significant transformation. Understanding the impact of land use change on carbon storage helps formulate reasonable land management policies and provides data support for climate change mitigation.

Land use change affects terrestrial ecosystem carbon storage by altering ecosystem distribution patterns and soil respiration rates. For instance, Li et al. used the InVEST model to estimate terrestrial ecosystem carbon storage in Hubei Province, finding that carbon storage decreased by 29.23 Tg between 2000 and 2020, primarily due to the conversion of high carbon density land types such as forest land to construction land. The scale of construction land expansion directly affects the rate of carbon storage change. Zhu et al. assessed ecosystem carbon storage based on land use change scenarios, concluding that the degradation of forest land and grassland was the main reason for decreased carbon density, which has important implications for rational regional land use planning. In this study, grassland, as the main land use type in the Qilian Mountain region, serves as the primary carbon pool and plays a crucial role in the terrestrial ecosystem. This conclusion is consistent with previous research on carbon storage changes in the Qilian Mountain region, which found that carbon storage in the area shows an overall increasing trend. This increase can be attributed to two main factors: first, the conversion of low carbon density unused land to higher carbon density grassland, water bodies, and cultivated land, which enhances terrestrial ecosystem carbon storage capacity; second, the implementation of national wildlife protection laws and the Natural Forest Protection Program, which have reduced human activities through measures such as closing mountains for afforestation and prohibiting grazing, thereby protecting lands with strong carbon sequestration capacity. However, carbon storage in the Qilian Mountain region experienced a slight decline during 2010–2015 due to accelerated urbanization and construction land expansion occupying large areas of water bodies and unused land, demonstrating that conversion of other land types to construction land significantly reduces terrestrial carbon storage capacity.

Furthermore, the Qilian Mountain region in northwestern China, as a climate-sensitive area with fragile ecological environments, faces dual pressures from climate change and human activities. Although this study indicates that local ecosystem carbon storage has increased overall, the region’ s unique geographic features and climatic conditions make it vulnerable to land degradation and biodiversity loss. Therefore, establishing a long-term land use change monitoring system is essential. As climate change intensifies and socioeconomic development demands increase, land use change will likely accelerate. Future land management decisions must comprehensively consider social, economic, and climatic factors, and predict terrestrial carbon storage under different development scenarios in the Qilian Mountain region, which is crucial for increasing carbon storage and environmental protection.

3.2 Analysis and Significance of Carbon Storage Economic Value

In recent years, as global climate change has become increasingly severe and carbon trading markets have gradually developed, the importance of estimating the economic value of terrestrial ecosystem carbon storage has become more prominent alongside its ecological value. China possesses enormous carbon emission resources; however, its carbon trading market started late and has developed slowly, without forming a mature trading system. Currently, there is no unified standard for carbon pricing, and different methods yield significantly different estimates of carbon storage economic value. For example, Hu et al. estimated the economic value of carbon storage in Sichuan Province using the willingness-to-pay method at 865.75$×10^{6}$ yuan, while the afforestation cost method yielded an estimate of 423.6$×10^{6}$ yuan. Zhang et al. estimated the carbon sink economic value of Kunming Xishan Forest Park using the afforestation cost method at 1517.55$×10^{6}$ yuan, while applying the Swedish carbon tax rate gave a total carbon sink value of 1591.10$×10^{6}$ yuan.

Unlike previous studies, this research is the first to use the compound present value method, widely applied in financial management and engineering economics, to estimate the economic value of carbon storage in the Qilian Mountain region. Between 2000 and 2020, both carbon storage and its economic value in the Qilian Mountain region showed increasing trends, consistent with the findings of Yu et al., which indirectly confirms the enhancement of local ecosystem functions and environmental service capacity. Carbon storage economic value is determined by both carbon storage quantity and carbon sequestration price. Since carbon prices are identical within the same period, carbon storage quantity is the key factor determining carbon economic value. However, it is important to note that while carbon storage decreased slightly during 2010–2015, carbon storage economic value continued to increase. This can be attributed to two factors: first, although carbon storage declined, rising carbon prices increased the value per unit of carbon, thereby increasing overall economic value; second, the rate of carbon price increase far exceeded the rate of carbon storage decline. This demonstrates that under certain conditions, decreased carbon storage does not necessarily lead to decreased economic value, as carbon price and discount rate factors may combine to increase carbon storage economic value.

Carbon storage economic value plays a crucial role in both environmental and economic domains, providing a foundation for assessing carbon resource potential, promoting carbon emission reduction initiatives, facilitating carbon market development, and informing policy formulation. Future efforts should focus on establishing and implementing carbon pricing mechanisms, increasing investment in low-carbon technology research and development, and building partnerships among stakeholders to improve global carbon market trading. Additionally, governments can protect and restore carbon-intensive ecosystems such as forests, wetlands, and oceans, and strengthen land management and protection to ensure proper conservation and management of soil organic carbon.

4 Conclusion

Based on five periods of land use data from 2000 to 2020 in the Qilian Mountain region, this study analyzed land use change characteristics using land use transfer matrices and dynamic degree methods, assessed terrestrial ecosystem carbon storage using the InVEST model, and estimated changes in carbon storage economic value by integrating the compound present value formula. The main conclusions are as follows:

1. Grassland and unused land accounted for over 80% of the total area and were the main land use types in the Qilian Mountain region during 2000–2020, with relatively significant conversion between them. Due to urbanization advancement and the region' s special geographic characteristics, land use types in the Qilian Mountains showed expansion in cultivated land, grassland, water bodies, and construction land, while forest land and unused land areas contracted.

2. Carbon storage in the Qilian Mountain region increased by 44.26$\times10^{4}$ t from 2000 to 2020, with a growth rate of 68.1%, exhibiting a "low in the northwest and high in the southeast" spatial distribution pattern that gradually increased along the southeast direction. This was attributed to the region' s suitable climate characteristics and industrial structure, which led to substantial grassland expansion as the main reason for increased carbon storage. Specifically, cultivated land, grassland, and water bodies increased carbon storage by 73.1$\times10^{4}$ t, while forest land and unused land decreased carbon storage by 28.8$\times10^{4}$ t.

3. The economic value of carbon storage in the Qilian Mountain region increased from 2325.9$\times10^{6}$ yuan to 3908.8$\times10^{6}$ yuan between 2000 and 2020, with an increment of 1582.9$\times10^{6}$ yuan and a growth rate of 68.1%. The proportions of carbon storage economic value by land use type were: grassland 51.9%, forest land 19.9%, unused land 18.6%, and cultivated land 2.98%. Grassland carbon storage economic value was the largest, while cultivated land carbon storage economic value was the smallest, and the increase in grassland carbon storage economic value was the main driver of increased carbon economic value in the Qilian Mountain region.

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