Coupling Relationship between Climate Change, Landscape Pattern and Ecosystem Carbon Storage: A Case Study of the Qilian Mountains (Postprint)

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Abstract

Climate change and landscape patterns are intimately linked to the structure, function, and dynamic variations of ecosystems. The Qilian Mountains ecosystem (QLME) constitutes a crucial ecological functional zone in China. Leveraging multi-source data, remote sensing and GIS technologies, in conjunction with InVEST and GeoSOS-FLUS models, this study explores CSET and methods to estimate carbon storage within the QLME. Quantitative estimation and analysis reveal that: (1) Carbon storage in the QLME demonstrates pronounced spatiotemporal heterogeneity across different landscape type contexts, with the highest carbon storage observed in grassland and forest landscapes, followed by bare land, while cropland, wetland, construction land, and rural residential landscapes exhibit relatively low carbon storage. During 1985–2018, overall carbon storage in the QLME exhibited an increasing trend, rising by 4805.95$×$104 t with an annual growth rate of 38.43%. (2) Carbon storage in grassland landscapes accounts for over 50% of the study area, displaying a trend of initial increase followed by subsequent decrease; carbon storage in forest landscapes comprises 11.31%~36.16% of total carbon storage, with substantial variation. (3) Under future RCP4.5 and RCP8.5 climate change scenarios, carbon storage in the QLME tends toward increase, with projected average carbon storage of 3813.38 t · km-2 by 2050, representing an 8.69% increase relative to 2018. This research holds significant importance for advancing understanding of carbon cycling mechanisms and ecosystem stability.

Full Text

The Coupling Relationship between Climate Change, Landscape Pattern and Ecosystem Carbon Storage: A Case Study of the Qilian Mountains

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Abstract: Climate change and landscape pattern are closely related to ecosystem structure, function, and dynamic changes. The Qilian Mountain Ecosystem (QLME) represents an important ecological functional zone in China. Based on multi-source data and utilizing remote sensing and GIS technology combined with InVEST and GeoSOS models, this study explores methods for estimating carbon storage across different landscape types. Quantitative estimation and analysis reveal that carbon storage in the QLME exhibits significant spatiotemporal heterogeneity. The highest carbon storage occurs in grassland and forest landscapes, followed by bare land, while cultivated land, wetland, construction land, and rural residential landscapes show relatively low carbon storage.

From 1985 to 2018, overall carbon storage in the study area displayed an increasing trend, rising by 4805.95$×$10 with an annual growth rate of 38.43%. Grassland carbon storage accounts for over half of the study area, following a pattern of initial increase followed by decrease. Forest landscape carbon storage comprises 11.31%~36.16% of total carbon storage, showing substantial variation. Under future climate change scenarios (RCP4.5 and RCP8.5), carbon storage is projected to increase, with average carbon storage estimated at 3813.38 t · km for 2050, representing an 8.69% growth rate. This research provides important insights for understanding carbon cycling dynamics and ecosystem stability.

Keywords: Qilian Mountain Ecosystem (QLME); climate change scenario; carbon storage estimation technology (CSET); ecosystem service value assessment technology; landscape pattern; model

Introduction

Under the background of global change, ecosystems have undergone a series of transformations. United Nations programs have provided an important foundation for scientific understanding of ecosystem structure, function, and dynamic changes, supporting research on ecological process mechanisms, ecosystem service function assessment, and carbon source-sink monitoring and analysis. With increasing attention to carbon emission reduction, carbon peak, and carbon neutrality, the role and status of mountain ecosystems in global change have gained prominence. The Qilian Mountains serve as an important ecological barrier in the arid regions of western China, and maintaining regional ecosystem functions is of vital importance for ecological construction, environmental protection, and socio-economic development in this region and related areas.

Various methods have been explored for ecosystem service value assessment and carbon storage estimation, including value assessment methods, energy analysis methods, and ecological model methods. With advances in ecological informatics, environmental informatics, and geographic information science, ecosystem service assessment methods and carbon storage estimation methods have become increasingly integrated with ecological models. Currently, widely used models include InVEST, ARIES, and SoLVES, among which the InVEST model is extensively applied. In practical applications, InVEST' s numerous modules are categorized into different types: one type supports ecosystem service function modules such as habitat quality and habitat risk assessment, while another type includes final ecosystem service modules encompassing carbon storage, water conservation, water purification, and soil retention.

Under climate change scenarios, although temperature controls soil organic carbon storage in mid-to-high latitude regions, hydroclimate in tropical regions may be the main driver of soil carbon retention. Global forest ecosystem carbon pools exhibit extreme complexity, and forest water use efficiency is closely related to carbon storage. Model simulation methods play an important role in estimating ecosystem parameters. In recent years, intensified human activities such as climate change, overgrazing, mining, illegal construction, and tourism have caused degradation of natural forest and grassland vegetation, frequent soil erosion, shrinking ice and snow cover, and reduced biodiversity in the Qilian Mountains.

The Qilian Mountain Ecosystem (QLME) encompasses diverse resources and vegetation types, including Qinghai spruce (Picea crassifolia), Qilian juniper (Sabina przewalskii), and shrubs such as Potentilla and Salix. Against the backdrop of national strategic decisions to curb ecological environment deterioration in the Qilian Mountains, further research on the dynamic changes of ecological service functions and carbon storage estimation at different spatiotemporal scales under climate change scenarios is essential for comprehensively revealing the comprehensive environmental effects of the QLME. This study also holds important theoretical value for exploring the impacts of climate change and landscape pattern on carbon storage, as well as for developing a series of technical systems for mountain ecosystem environmental evolution and quality assessment, including ecosystem service value estimation technology and ecosystem habitat quality evaluation technology. In the long term, it also has significant practical implications for the construction of nature reserves centered on national parks and for green, low-carbon development advocated by the state.

1 Study Area and Data Sources

The Qilian Mountain Ecosystem (QLME) studied in this research is located at the intersection of the Qinghai-Tibet, Loess, and Mongolian-Xinjiang plateaus, with geographical coordinates of 95°06 ~103°01 E and 36°40 ~39°42 N, covering a total area of 5.02$×10km^{2}$. The region features a mountain-canyon geomorphology, higher in the west and lower in the east, with elevations ranging from 1767 to 5604 m. The area encompasses various ecological landscape types including forest, grassland, wetland, desert, and glacier-snow cover. The northern part along the Hexi Corridor has a typical temperate continental climate, while the southern part belongs to the alpine semi-arid climate, with annual precipitation of 96.4~729.6 mm showing large spatiotemporal variation. As the water source area for many river systems including the Heihe, Shule, and Shiyang rivers, the region has unique patterns of water resource formation, transformation, and consumption. Glaciers, snow cover, and forest ecosystems provide important water conservation services.

Soil types include black felty soil, cold calcic soil, and frozen soil among others. Vegetation shows vertical landscape distribution patterns along different altitude gradients. From low to high elevation, natural landscape zones include mountain forest belts, mountain grassland belts, subalpine shrub belts, subalpine meadow belts, and alpine sparse vegetation belts with ice and snow. Vegetation consists mainly of Qinghai spruce, Qilian juniper, and shrubs such as Potentilla and Salix.

To meet the requirements of the models, various data sources were collected and preprocessed. Meteorological data and future climate scenario data were obtained from the China Meteorological Data Sharing Service System. Annual precipitation and annual potential evapotranspiration raster data were processed through interpolation using the Penman-Monteith method and ANUSPLIN software. Land use/cover data, plant available water content, and soil maximum root depth raster data were acquired from the National Tibetan Plateau Science Data Center and processed through reclassification and resampling using ArcGIS software. Secondary watershed boundary vector data and DEM raster data were obtained from the Resource and Environmental Science Data Cloud Platform and processed using ArcGIS hydrological analysis modules. Based on DEM data, slope and aspect raster data were generated using ArcGIS 3D Analyst tools. Vector data for roads, railways, and urban residential areas were sourced from the National Fundamental Geographic Information Database, and Euclidean distances were calculated using ArcGIS distance analysis modules. In addition to basic information on different ecological landscape types obtained from field surveys, a series of multi-source data were employed for carbon storage estimation and analysis. According to the basic data requirements of the GeoSOS and InVEST models, various data underwent different preprocessing procedures before being used to further invert relevant ecological landscape elements through the models.

2 Research Techniques and Methods

Based on the natural geographical conditions of the study area and remote sensing geological analysis, combined with macro-scale surveys and typical studies, ecosystem attribute characteristics were obtained to estimate ecosystem carbon storage and analyze its environmental effects through the InVEST model.

2.1 Carbon Storage Estimation Technology (CSET)

For carbon storage estimation, based on the InVEST model, this study explores methods to estimate carbon storage in mountain ecosystems. Specifically, the carbon storage module in the InVEST model is divided into four basic carbon pools: aboveground biomass carbon, belowground biomass carbon, soil carbon, and dead organic matter carbon. To estimate carbon storage in various forms, different types of data support are required. Based on the aforementioned data sources and the characteristics of the InVEST model, ecosystem structure was analyzed to quantitatively estimate carbon storage. The average carbon densities of these four carbon pools were statistically determined, then multiplied by the area of each land use type and summed to obtain the total carbon storage of the study area.

In fact, the reasons for spatiotemporal differences in carbon storage are complex, with both natural factors and human activities having different impacts. From a temporal perspective, as mentioned above, the coniferous trees are mainly Qilian juniper and Qinghai spruce, while shrubs and herbaceous plants in this ecosystem have been under protection for many years due to national ecological environmental protection policies and forestry management strategy adjustments. Meanwhile, regional hydrological, climatic, and soil conditions have adapted to these changes over the long term, and biomass in living organisms has a cumulative effect. As carbon is the main component of biomass, carbon storage is generally in an increasing trend under this background. In particular, carbon storage in a certain year reached its maximum value since a previous period. However, around this period, disorderly mining, large-scale tourism, and overgrazing directly caused damage to ecosystem structure, leading to ecosystem dysfunction and reduced carbon storage effects. After 2017, the state strictly implemented the Qilian Mountains Nature Reserve remediation strategy, curbing unreasonable human behaviors, and the ecosystem structure was gradually regulated, with vegetation productivity gradually recovering.

The multi-year average carbon storage was 14151.56$×10, *withanannualgrowthrateof*38.43×10*atarateof*10.23 at a rate of 73.38%. The average carbon storage densities were 2520.08 t · km, 2693.83 t · km, and 3513.08 t · km respectively.

2.2 GeoSOS-FLUS Model Method

The GeoSOS model mainly consists of two modules: one is the suitability probability calculation module based on artificial neural networks; the other is the cellular automata module established according to an adaptive inertia mechanism. In the suitability module, land use classification data for a certain period in the study area and land use change driving factors (such as terrain, residential points, road distribution, etc.) are input, and the suitability probability of each land type in the study area is calculated through artificial neural networks. Then the land use status of a certain year is simulated and compared with actual land use data for verification.

3 QLME Carbon Storage Characteristics Analysis

3.1 Spatiotemporal Variation Characteristics of Carbon Storage

Using the methods described above, carbon storage in different years was estimated. shows the change characteristics of QLME carbon storage in different years.

After 2017, a series of strategies for ecological environment remediation in the Qilian Mountains were effectively implemented, and ecological functions were restored to a certain extent. However, the carbon storage has still not reached the level of a previous year. Investigations show that by August 2021, the habitat of Qilian Mountains had been significantly restored, and various human activities detrimental to ecological effects have been completely prohibited. Currently, integrated information networks and monitoring points cover the nature reserve, greatly promoting the restoration of ecological functions. With the advancement of green, low-carbon, high-quality development concepts and models, future carbon storage in the QLME is expected to further increase.

From a spatial perspective, as shown in Figure 2, carbon storage high-value areas exhibit a "central belt-shaped—southeastern patchy" distribution, with scattered point-shaped high-value areas in the northwest. The belt-shaped area refers to the interlaced distribution of forest and grassland landscapes in the central region; the southeastern patchy distribution mainly consists of concentrated forest and grassland landscapes; and the scattered point-shaped areas in the northwest are mostly low-coverage grassland landscapes in high-altitude areas of the Qilian Mountains. The reasons for spatial differences in carbon storage are mainly due to regional natural geographical characteristics.

In the Qilian Mountains region, different areas' terrain, landforms, soils, hydrology, and climate characteristics have nurtured specific natural geographical landscape zonations, particularly forming adapted plant geographical types. The vegetation characteristics described above are the result of long-term adaptation between plants and their habitats, containing the cumulative effects of biological productivity and its spatial differences. Since carbon storage status is directly related to biological productivity, this natural geographical spatial variability forms the spatial differences in regional carbon storage characteristics.

3.2 Carbon Storage Characteristics of Different Ecological Landscape Types

Differences in ecological landscape types characterized by land use/cover change constrain the spatiotemporal variation characteristics of carbon storage. Figure

3 shows carbon storage changes under different land use types in the study area over the years.

Carbon storage is highest in grassland and forest, followed by bare land, while cultivated land, wetland, construction land, and rural residential areas have relatively low carbon storage. The conversion of different landscape types leads to interannual variation trends in carbon storage, but they remain important carbon sinks. This is one of the important characteristics of carbon storage in the QLME. It should be noted that grassland landscape carbon storage accounts for more than half of the study area' s carbon storage, with significant changes over the years, showing a trend of first increasing then decreasing. Forest landscape type is also an important carbon sink in the study area, with its carbon storage accounting for 11.31%~36.16% of total carbon storage, showing large variation amplitude. Specifically, forest landscape carbon storage decreased significantly, reflecting certain destruction or degradation of forests in the study area. After 2017, forest landscape carbon storage increased significantly, which is directly related to the implementation of ecological restoration policies in recent years. Additionally, wetland landscapes in the QLME are mainly herbaceous wetlands with relatively high carbon density, but their contribution to carbon storage is relatively small due to their small area.

Research analysis shows that carbon storage differences contained in different ecological landscape types are concrete manifestations of the coupling relationship between natural and human factors.

4 Carbon Storage Changes Under Future Scenarios

4.1 Future Ecological Landscape Dynamics

Based on the principles and methods of the GeoSOS-FLUS model, land use types are used to represent ecological landscape types. The model is used to simulate land use/cover conditions for 2050. The model is calibrated to obtain suitability probabilities, and then land use status is simulated and compared with actual land use data for verification. The Kappa coefficient of verification results is [value], and the overall simulation accuracy is [value], indicating the model can effectively simulate changes in ecological landscape types in the QLME.

Specifically, using 2018 land use as the initial year and 2050 as the target year, the Markov Chain model is used to calculate transition probabilities for each land use type, thereby predicting land use structure and quantity for 2050. On this basis, 2018 land use data and driving factor data are used as input for the GeoSOS-FLUS model. Under the nature protection scenario, the land use status for 2050 is simulated.

The land use type transition matrix from 2018 to 2050 is shown in Table 2. Specifically, 1.96% of cultivated land transitions to bare land; grassland transitions include [transitions]; 8.79% transitions to glacier-snow landscape; 0.18% of bare land transitions to forest landscape, 1.17% of bare land is restored to grassland, and 1.09% of bare land transitions to glacier-snow landscape. Additionally, glacier-snow transitions include 21.38% conversion to grassland and 2.03% conversion to bare land. Due to the large base area of grassland and bare land landscapes, most converted landscape types are fragmented alpine meadows and low-coverage grasslands. Overall, land use spatial changes in the QLME from 2018 to 2050 show a positive development trend, with increased forest landscape area.

4.2 Carbon Storage Changes in QLME Under Future Scenarios

Climate models are important tools for future climate change research. In recent years, various climate models have emerged, such as CanESM2 and CSM1.1. The development of scenario models along the Belt and Road provides important reference for emission reduction. Considering the simulation capabilities of existing models, this study adopts climate change scenarios RCP4.5 and RCP8.5.

Using the land use type data obtained from simulation and forecasting, coupled with the InVEST model, the spatial distribution of carbon storage for 2050 is projected (Figure 5). It can be seen that average carbon storage is mainly concentrated in vegetation-covered areas in the eastern and central regions.

Figure 4 shows the spatial distribution characteristics of land use transfer in QLME from 2018 to 2050. The transition of grassland types and the transformation of bare land types are very obvious. In the central and eastern regions, large areas of grassland are converted to forest land; in addition, bare land in these areas is largely restored to forest and grassland, with significant increases in vegetation area. In high-altitude areas, the main transformations are between bare land and glacier-snow landscapes, as well as the restoration of glacier-snow landscapes and bare land to grassland.

Under the RCP4.5 and RCP8.5 climate scenarios, the average carbon storage of the study area is projected to be 3813.38 t, with total carbon storage of 18941.82$×$10 and an annual growth rate of 8.69%. The QLME ecosystem provides a series of ecological service functions. Based on climate change scenarios, exploring ecosystem service function model simulation techniques, especially the expansion of quantification, has important theoretical value and practical significance for understanding the characteristics and laws of carbon cycling and carbon sequestration.

Figure 5 shows the projected spatial distribution of carbon storage in QLME in 2050. It can be seen that carbon storage shows an increasing trend over time, especially after ecological restoration and management after 2017, carbon storage has been significantly improved. Under the nature protection scenario, forest area has increased significantly, so carbon storage will further increase by 2050.

Based on the analysis of carbon storage driving factors and coupling relationships, using the InVEST model to analyze the spatiotemporal evolution and variation patterns of carbon storage functions, and coupling with the GeoSOS model to project changes in carbon storage functions under future scenarios, the main findings are as follows: 1) Carbon storage varies across different periods; 2) Overall, carbon storage function in the study area shows an upward trend from 1985 to 2050, reflecting the comprehensive effects of natural and human factor coupling; 3) Different ecological landscape types correspond to significant differences in carbon storage; 4) Under future climate change scenarios, carbon storage tends to increase.

5 Conclusions

The Qilian Mountains constitute an important ecological security barrier in western China, a crucial water source area for the Yellow River basin, and a priority region for biodiversity protection in China. As a national key ecological function area and a pilot zone for national park construction, it plays an irreplaceable role in maintaining ecological stability and ensuring ecological security.

Based on the analysis of carbon storage driving factors and coupling relationships, using the InVEST model to analyze the spatiotemporal evolution and variation patterns of carbon storage functions, and coupling with the GeoSOS model to project changes in carbon storage functions under future scenarios, the main findings are as follows:

1) Carbon storage varies across different periods. From 1985 to 2050, the carbon storage function in the study area generally shows an upward trend, reflecting the comprehensive effects of coupling between natural and human factors.
2) Different ecological landscape types correspond to significant differences in carbon storage. In the QLME, ecological landscape types represented by land use have undergone a series of complex changes driven by natural and human factors, which are comprehensively reflected in the spatiotemporal characteristics of carbon storage. From different cover conditions, carbon storage from high to low is: grassland landscape, forest landscape, bare land landscape, wetland landscape, and other landscapes.
3) Under future climate change scenarios, carbon storage tends to increase. Under the RCP4.5 and RCP8.5 scenarios, using current technical means and based on model suitability and reliability calibration and analysis methods, carbon storage in 2050 shows varying degrees of increase, particularly demonstrating a growth trend.

This study provides important theoretical and practical significance for understanding carbon cycling dynamics and ecosystem stability, and offers technical support for the construction of nature reserves and low-carbon development.

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