ChinaRxiv 中X

AI translation · View original & related papers at
chinarxiv.org/items/chinaxiv-202602.00026

Spatiotemporal characteristics and future evolution trends of the carbon budget in the Mu Us region based on land-use change (postprint)

Authors: Zhang Xinyu, Ma Xuechun, Hu Ruichao, Li Pei, Wang Zhoufeng, Zhao Xiaohong, Xueping Wang, Zhang Xuanming

Date: 2026-01-30T16:53:16+00:00

Abstract

The dynamic response of carbon stocks in arid and semi-arid ecosystems remains a weak link in terrestrial carbon cycle research, particularly in ecologically fragile regions subject to intense human disturbance. As a typical ecological restoration area in northern China, the Mu Us region has undergone significant land-use transformation, yet the mechanisms by which these transformations affect the regional carbon budget remain unclear. This study analyzes the spatiotemporal evolution of land use and the changes in carbon budget patterns (carbon emissions, carbon stocks, and carbon balance) in the Mu Us region from 1990 to 2023. Using a geographical detector, we identify the potential driving factors of regional carbon balance, and further project land use and carbon budget under four scenarios—natural development, economic development, ecological conservation, and cultivated land protection. The results show that: (1) From 1990 to 2023, the areas of cropland, forest land, and impervious surfaces in the Mu Us region increased, while the area of bare land decreased. (2) Between 1990 and 2023, carbon emissions in the study area increased by 1.84$\times 10^6 t, carbonstocksincreasedby 5.86\times$10^7 t, and the carbon balance index was much greater than 1, indicating that the region functions as a carbon sink. (3) Potential evapotranspiration is the primary driver of the regional carbon balance, and the interactions among mean annual precipitation, slope, potential evapotranspiration, and plantation area exert a significant influence on regional carbon balance. (4) Under the ecological conservation, natural development, economic development, and cultivated land protection scenarios for 2035, cropland area in the study region exhibits an expanding trend, and carbon stocks under all four scenarios increase relative to 2023; carbon emissions under the economic development scenario exceed those in 2023. These findings provide support for maintaining the crucial role of arid and semi-arid

regions as ecological protection barriers and for achieving low-carbon, circular development.

Full Text

Arid Zone Research, Vol. 43, No. 1, January 2026

DOI: 10.13866/j.azr.2026.01.18
CSTR: 32277.14.AZR.20260118

Spatiotemporal Characteristics and Future Evolution Trends of the Carbon Budget in the Mu Us Region Based on Land Use Change

ZHANG Xinyu[1], MA Xuechun[1], HU Ruichao[1], LI Pei[1,2,3], WANG Zhoufeng[1,2,3], ZHAO Xiaohong[2,4], WANG Xueping[1,2,3], ZHANG Xuanming[1,2,3]

[1]School of Water and Environment, Chang'an University, Xi'an, Shaanxi, China
[2]Key Laboratory of Subsurface Hydrology and Ecological Effect in Arid Region, Ministry of Education, Xi' an, Shaanxi, China
[3]Key Laboratory of Ecological Hydrology and Water Security in Arid Region, Ministry of Water Resources, Chang' an University, Xi' an, Shaanxi, China
[4]School of Civil Engineering, Chang' an University, Xi' an, Shaanxi, China

Abstract

The dynamic response of ecosystem carbon storage in arid and semi-arid regions represents a weak link in terrestrial carbon cycle research, particularly in ecologically fragile zones experiencing intensive human intervention. As a typical ecological restoration area in northern China, the mechanisms through which land-use transformation affects the carbon budget in the Mu Us region remain unclear. This study analyzed the spatiotemporal evolution characteristics of land use and changes in the carbon budget (carbon emissions, carbon storage, and carbon balance) patterns in the Mu Us region from 1990 to 2023, employed Geodetector to identify potential influencing factors affecting the regional carbon balance status, and predicted land use and carbon budget under four scenarios: natural development, economic development, ecological protection, and cultivated land protection. The results show that: (1) From 1990 to 2023, the areas of cropland, forestland, and impervious surfaces increased, while bare land area decreased. (2) Carbon emissions increased by 1.84×10^6 t and carbon storage increased by 5.86×10^7 t from 1990 to 2023. The carbon balance index greatly exceeded 1, indicating that the region functions as a carbon sink. (3) Potential evapotranspiration is the primary driving factor affecting the regional carbon balance status, and the interactions among annual average precipitation, slope, potential evapotranspiration, and artificial forest area have significant effects on the regional carbon balance. (4) Under all four scenarios, by 2035, the area of cropland is projected to expand and carbon storage increases, while carbon emissions are higher under the economic development scenario compared to 2023. The research findings provide support for maintaining the important status of ecological protection barriers in arid and semi-arid regions and achieving low-carbon circular development.

Keywords: carbon budget; land use type; driving factors; Mu Us region; PLUS-InVEST-Geodetector model

1 Introduction

Global climate change has become one of the major challenges facing humanity in the 21st century. Terrestrial ecosystem carbon cycling is a key process regulating atmospheric CO_2 concentrations, and increasing carbon sinks is considered an important pathway to mitigate global warming. Arid regions constitute an important component of terrestrial ecosystems, covering approximately 41% of global land area and storing about 27% of soil organic carbon. These regions feature fragile ecosystems with complex carbon sink functions, playing a unique role in global carbon balance. However, the spatiotemporal evolution of carbon budgets in arid and semi-arid regions and their response mechanisms to land use changes have not been fully revealed, which constrains the formulation of regional carbon management strategies to some extent.

Land Use/Cover Change (LUCC) is a key pathway through which human activities affect terrestrial carbon cycling and represents the second-largest anthropogenic carbon emission source after fossil fuel combustion. In recent years, some scholars have estimated carbon storage in terrestrial ecosystems such as forests, grasslands, and croplands based on long time-series land use data, remote sensing inversion, and ecosystem models (e.g., InVEST model), and combined PLUS and other models for regional or watershed-scale carbon storage prediction. Although these studies can reasonably reflect the total carbon stock and accumulation in regional ecosystems, their prediction time points mostly focus on the period after 2000, with less consideration of the long-term impacts of key ecological projects from the last century on land use types and carbon storage in arid and semi-arid regions. Moreover, using carbon storage alone cannot comprehensively characterize the carbon source-sink function of ecosystems. In contrast, introducing carbon budget and carbon balance index can more intuitively evaluate carbon source-sink functions. Additionally, existing studies have mainly analyzed the influence of environmental factors on regional carbon storage changes from natural factor perspectives, emphasizing the contributions of elevation, precipitation, and other natural conditions, whereas carbon storage changes in arid and semi-arid regions often result from the combined effects of socioeconomic activities and related policy implementations. Therefore, systematically assessing land use change and its impacts on carbon emissions, carbon storage, and carbon balance status is a critical entry point for understanding carbon budget dynamics in arid and semi-arid regions.

The Mu Us Sandy Land is one of China’ s four major sandy lands, located at the intersection of Shaanxi Province, Inner Mongolia Autonomous Region, and Ningxia Hui Autonomous Region [Figure 1: see original paper], situated in a transitional zone from arid to semi-arid climate. It represents a typical ecologically fragile area where human activities and ecological vulnerability are coupled. The region has low vegetation coverage but high deep soil carbon density, exhibiting typical carbon pool characteristics of arid zones. Over the past several decades, large-scale ecological restoration projects have reversed the trend from “sand encroachment and human retreat” to “green advancement and sand retreat” in this region. The dramatic changes in land use patterns provide an important case for analyzing carbon storage evolution under human intervention. Therefore, this study takes the Mu Us region as the research object, analyzes land use type and carbon budget spatiotemporal evolution patterns from 1990 to 2023, employs Geodetector to analyze main driving factors affecting regional carbon budget, uses the PLUS model to simulate and predict land use patterns under natural development, economic development, ecological protection, and cultivated land protection scenarios, and further estimates carbon budget evolution caused by land use changes. The study aims to reveal potential impacts on carbon budgets over the next 12 years, providing scientific support for ensuring regional ecological security and optimizing land use structures under the guidance of the “dual carbon” strategic goals.

1.1 Study Area Overview

The study area is located in the Mu Us region (37°20′~39°23′N, 107°20′~111°30′E) at the intersection of Shaanxi Province, Inner Mongolia Autonomous Region, and Ningxia Hui Autonomous Region [Figure 1: see original paper]. The terrain gradually slopes from northwest to southeast. Regional annual precipitation ranges from 137 to 578 mm, with large interannual variability and uneven distribution, concentrating in July-September and accounting for approximately 60-80% of annual precipitation. The average annual temperature is 6.8~10.9°C, and the multi-year average surface evaporation is about 1200 mm. Vegetation shows zonal distribution, transitioning from desert steppe in the northwest to dry steppe and forest steppe in the southeast. The region has low vegetation coverage but high deep soil carbon density, exhibiting typical carbon pool characteristics of arid zones.

1.2 Data Sources and Processing

Data used in this study include land use type, annual average temperature, annual average precipitation, potential evapotranspiration (PET), Normalized Difference Vegetation Index (NDVI), slope (calculated from DEM data), nighttime light, artificial forest area, etc. Data types and sources are detailed in . To balance spatial resolution and processing efficiency, data were resampled to a resolution of 30 m × 30 m using the nearest neighbor method.

1.3 Methods

1.3.1 Land Use Transfer Matrix and Prediction (1) Land Use Transfer Matrix. The land use transfer matrix was used to calculate the sources, destinations, transfers, and conversions of land use types in the study area from 1990 to 2023, clarifying the spatiotemporal evolution patterns of land use types in the region.

(2) Land Use Type Prediction. Following the methodology of Bi Fanfan et al., transfer matrices and neighborhood weights were established to set four development scenarios: natural development, economic development, ecological protection, and cultivated land protection. Under the natural development scenario, land use evolution trends from 1990 to 2023 were continued to predict land use structure for 2035. The economic development scenario emphasized economic growth, imposing no restrictions on impervious surface development and allowing all land types except water bodies to convert to impervious surfaces. The ecological protection scenario prioritized the development of ecological land such as forestland, grassland, and water bodies, strictly controlling their conversion to impervious surfaces. The cultivated land protection scenario prohibited the conversion of cropland to other land types.

The PLUS model employs a land expansion analysis strategy and a multi-class random patch seed-based cellular automata model to mine driving factors of land expansion and landscape changes, thereby simulating the generation and evolution of land use patches. Compared with other models, the PLUS model' s advantage lies in its ability to identify driving factors of land expansion and landscape dynamics, enabling patch evolution prediction under different land use scenarios.

1.3.2 Land Use Carbon Budget Calculation and Prediction (1) Carbon Emission Calculation. The carbon emission factor method was used to calculate carbon emissions, i.e., multiplying the area of different land types by corresponding carbon emission factors to obtain the total carbon emissions from each land type. The formula is: $CE = \sum(x_i \times c_i)$, where CE represents direct carbon emissions from land use (t), x_i represents the area of land type i (hm^2), and c_i represents the carbon emission coefficient for land type i. Based on previous research results, carbon emission coefficients for cropland, forestland, grassland, water bodies, impervious surfaces, and unused land were assigned values of 0.42, -0.64, -0.02, 0, 1.82, and 0.05 $t \cdot hm^{-2} \cdot yr^{-1}$, respectively.

(2) Carbon Storage Calculation. The InVEST model is a comprehensive model for evaluating ecosystem services and trade-offs, applied to estimate ecosystem carbon storage. The model divides ecosystem carbon storage into aboveground biomass carbon, belowground biomass carbon, soil carbon, and dead organic carbon. The carbon storage formula is: $CS = \sum(C_{i\_above} + C_{i\_below} + C_{i\_soil} + C_{i\_dead}) \times A_i$, where i represents a land use type; C_i represents carbon density for land use type i ($t \cdot hm^{-2}$); C_{i_above} represents aboveground vegetation carbon density for land use type i ($t \cdot hm^{-2}$); C_{i_below} represents belowground vegetation carbon density ($t \cdot hm^{-2}$); C_{i_soil} represents soil carbon density ($t \cdot hm^{-2}$); C_{i_dead} represents dead organic carbon density ($t \cdot hm^{-2}$); CS represents total ecosystem carbon storage (t); A_i represents the area of land use type i (hm^2); and n represents the number of land use types. Carbon density data () were referenced from similar regions and areas at the same latitude.

(3) Carbon Balance Analysis. The ratio of carbon storage to carbon emissions in the study area was used to reflect regional carbon budget balance status and carbon source-sink capacity. The formula is: $CO = CS/CE$, where CO represents the carbon balance index of the study area, CE represents direct carbon emissions from land use (t), and CS represents total ecosystem carbon storage (t).

1.3.3 Geodetector Geodetector is a method that reveals driving factors by detecting spatial stratified heterogeneity of elements. Spatial stratified heterogeneity refers to the phenomenon where the sum of within-layer variance is less than total between-layer variance, with its magnitude measured by the q-value of Geodetector. This study employed single-factor detection and interaction detection in Geodetector to analyze driving factors of carbon storage changes. Single-factor effects are measured by q-values ($0 \leq q \leq 1$), where larger q-values indicate greater explanatory power of the independent variable on spatial differentiation of the dependent variable. Interaction detection evaluates whether the explanatory power increases or decreases when two independent variables act together on the dependent variable.

Based on the study area' s current conditions, existing research foundations, and data availability, potential factors influencing regional carbon balance changes were selected, including natural factors (slope, annual average precipitation, potential evapotranspiration, NDVI) and socioeconomic factors (artificial forest area, nighttime light).

2 Results

2.1 Spatiotemporal Evolution of Land Use in the Mu Us Region

From 1990 to 2023, grassland was the dominant land use type in the Mu Us region (accounting for over 47.16%), and also the land type with the largest transfer-out area. The overall spatial pattern showed interlaced agricultural, forestry, and pastoral land use, decreasing bare land, and increasing grassland. Grassland was mainly distributed in the southern and eastern parts of the study area (Otog Front Banner, Yanchi County, Dingbian County, Hengshan District, and Yuyang District), while bare land was concentrated in the central and northern parts (Uxin Banner, Otog Banner, and western Shenmu City) [Figure 3: see original paper]. From 1990 to 2023, bare land area decreased by 72.40%, mostly converting to grassland; grassland mostly converted to cropland, with cropland area increasing by 16.20%. Additionally, although forestland, impervious surfaces, and water bodies accounted for small proportions, their areas continuously expanded, increasing by 1495.98 hm^2, 5395.32 hm^2, and 1627.56 hm^2, respectively. Under the impetus of the Three-North Shelter Forest Program and other policies, most bare land was replaced by grassland, cropland increased, water bodies, forestland, and impervious surfaces showed steady growth, and regional land use structure optimization and ecological restoration achievements were remarkable [Figure 2: see original paper].

2.2 Carbon Budget Spatiotemporal Pattern Simulation

From 1990 to 2023, carbon emissions in the Mu Us region increased from 2.37×10^6 t to 2.90×10^6 t, an increase of 1.84×10^6 t (346.76% increase, with an average annual increase of 3.82×10^4 t). Carbon storage increased from 3.15×10^8 t to 3.74×10^8 t, an increase of 5.86×10^7 t (18.10% increase, with an average annual increase of 3.24×10^5 t). Integrating carbon emission and carbon storage estimation and simulation results [Figure 4: see original paper], the carbon balance index of the study area in 1990 was 132.91, decreasing to 128.90 in 2023, a reduction of 13.61%. The carbon balance index showed a 逐年下降 trend, but remained much greater than 1, indicating that the study area belongs to a carbon sink functional zone.

2.3 Identification of Driving Factors of Carbon Balance in the Mu Us Region

Geodetector was used to identify driving factors of the spatial distribution pattern of the carbon balance index in the study area. Results [Figure 5: see original paper] showed that potential evapotranspiration is the main driving factor affecting the regional carbon balance status, with an explanatory power of 0.38. Annual average temperature (0.31) and slope (0.28) followed, while the influence of annual average precipitation was relatively weak (explanatory power below 0.20). Interaction detection results [Figure 5: see original paper] showed that the explanatory power of any two driving factors' interaction on the regional carbon balance index was significantly higher than that of single factors, showing a dual-factor enhancement effect. The most significant driving factor combination for explanatory power was annual average precipitation slope (0.62), followed by potential evapotranspiration annual average precipitation (0.58), annual average temperature artificial forest area (0.55), and potential evapotranspiration artificial forest area (0.54), all with explanatory powers above 0.50. This indicates that the regional carbon balance status is jointly affected by natural and anthropogenic factors.

2.4 Future Scenario Predictions

2.4.1 Land Use Type Prediction Using 2023 land use data as the initial condition, the PLUS model simulated land use spatial patterns for 2035 and validated model accuracy. Results showed a Kappa coefficient of 0.82, indicating high reliability for simulating 2035 land use. Simulation results under different scenarios [Figure 6: see original paper] showed that under ecological protection, natural development, economic development, and cultivated land protection scenarios, cropland area would expand, reaching 64427.94 hm^2, 51879.78 hm^2, 31835.79 hm^2, and 53565.21 hm^2, respectively. Under the ecological protection scenario, forestland would be effectively protected, reaching 63953.28 hm^2. Grassland area would increase under all four scenarios, while bare land area would generally decrease. Impervious surfaces would peak under the economic development scenario (63953.28 hm^2), while ecological protection and cultivated land protection scenarios would restrict impervious surface expansion, reducing areas by 5180.40 hm^2 and 8737.56 hm^2, respectively.

2.4.2 Carbon Budget Prediction Based on Land Use Change Carbon emissions under the four scenarios (ecological protection, natural development, cultivated land protection, and economic development) were 2.15×10^6 t, 2.02×10^6 t, 2.17×10^6 t, and 3.14×10^6 t, respectively, with only the economic development scenario showing higher emissions than 2023. Carbon storage across the four scenarios ranked from largest to smallest as: cultivated land protection scenario (389.08×10^6 t), natural development scenario (388.62×10^6 t), ecological protection scenario (388.59×10^6 t), and economic development scenario (387.56×10^6 t). All four scenarios showed carbon storage increases compared to 2023, with the cultivated land protection scenario showing the most significant increase of 6.89×10^6 t (1.84% increase). The economic development scenario showed the smallest carbon storage increase of 1.40%, reflecting that intensive development activities weaken the region' s carbon storage capacity. Among land types, grassland demonstrated the most prominent carbon storage capacity, accounting for approximately 47%–49% of total regional carbon storage, followed by cropland (17%–19%), while impervious surfaces had the lowest carbon storage capacity (0.08%–0.15%). The carbon balance index was highest under the cultivated land protection scenario (179.26), followed by natural development (179.21) and ecological protection (179.17) scenarios, with the economic development scenario being the lowest (123.43). Spatially, carbon storage changes under different scenarios showed coexistence of increases and decreases, distributed sporadically [Figure 7: see original paper]. Overall, under the cultivated land protection scenario, carbon storage increased significantly in Uxin Banner, Otog Banner, and Otog Front Banner. Under the economic development scenario, carbon storage loss was severe along the Baotou-Maoming Expressway and around the Shendong mining area in the central region, with noticeable decreases in Yuyang District and Jingbian County. Under ecological protection and natural development scenarios, carbon storage changes were significant in Uxin Banner, Otog Banner, and Otog Front Banner, while carbon storage remained basically stable in low-development areas at the edges of sandy land. Therefore, carbon storage changes in the study area are closely related to coal mining and agricultural development conditions in northern Shaanxi.

3 Discussion

3.1 Carbon Budget Evolution in the Mu Us Region

From 1990 to 2023, carbon storage in the Mu Us region showed a fluctuating upward trend, with carbon storage in 2035 under all four scenarios being higher than in 2023. This change aligns with carbon storage trends in other Chinese study areas, but differs from the "higher in southeast, lower in northwest" spatial distribution pattern on the Loess Plateau. As the most important carbon pool in the study area, grassland area continued to grow over the past 30+ years, increasing by 6.25×10^5 hm^2; most of this increased grassland was converted from bare land, thus bare land carbon storage showed an overall decreasing trend. Spatially, high carbon storage areas in the study region are mainly located in the northwestern Uxin Banner area, where land use type is predominantly grassland. Additionally, carbon storage growth areas highly coincide with artificial forest construction regions in northern Shaanxi. Field observations indicate that vegetation restoration significantly increased soil inorganic carbon, organic carbon, and stable components, enabling continuous accumulation of the regional carbon pool during the sand fixation process. For example, during vegetation restoration, total inorganic carbon in soils at different depths (0–10 cm, 10–20 cm, 20–55 cm) increased by 0.15–0.42 $g \cdot kg^{-1}$. Soil organic carbon in 20–50-year-old shrub forests increased significantly, with particulate component carbon density increasing rapidly, particularly prominent in the 0–20 cm soil layer. Recent surveys (2024) show that surface soil organic carbon content in shrub and arbor forests in the Mu Us region can reach 11.93–16.41 $g \cdot kg^{-1}$, with local enrichment in mid-deep soil layers; dissolved organic carbon in spring shrub forests can reach 72.43 $mg \cdot kg^{-1}$, and easily oxidized organic carbon content in grassland surface soils can reach 2.09 $g \cdot kg^{-1}$. These results further demonstrate that natural and anthropogenic factors jointly drive land use changes, especially the expansion of forestland and grassland areas, which significantly impact the regional carbon budget, leading to continuous increases in regional carbon storage.

3.2 Driving Factors of Carbon Balance in the Mu Us Region

Regional carbon storage is influenced by natural factors, human activities, and their interactions, with natural factors playing a dominant role. Potential evapotranspiration significantly affects the spatial distribution of the regional carbon balance status, being closely related to climatic conditions such as temperature and radiation. Larger regional potential evapotranspiration leads to greater ecosystem water stress, potentially limiting vegetation growth and carbon fixation capacity, thereby affecting the carbon budget. The interactions among annual average precipitation, slope, potential evapotranspiration, and artificial forest area also significantly affect the regional carbon balance. As the main water source for ecosystems, precipitation alleviates water deficits caused by potential evapotranspiration to some extent, facilitating vegetation photosynthesis and carbon absorption. Meanwhile, precipitation indirectly regulates vegetation productivity by interfering with physiological processes such as photosynthesis and transpiration. Slope can alter surface hydrothermal conditions and potential evapotranspiration, affecting vegetation growth, soil organic carbon accumulation, and regional carbon sequestration. In arid and semi-arid regions, areas with steep slopes are prone to soil erosion, with surface soil organic carbon migrating with runoff, showing a decreasing trend from hilltop to footslope, with maximum variation up to 15.95 $g \cdot kg^{-1}$. Additionally, slope drives vegetation type differentiation by affecting water, temperature, and light conditions, intensifying species competition and altering distribution patterns of artificial forests and natural vegetation, as well as the carbon sink structure of forest-grass systems. Artificial forests, as important anthropogenic factors, typically have high carbon sequestration potential, but their effects are constrained by hydrothermal conditions and topography. In areas with gentle slopes and adequate precipitation, artificial forest expansion can effectively enhance carbon sinks; while in areas with steep slopes, high potential evapotranspiration, and severe water deficits, even increased artificial forest area may not fully realize its carbon sequestration potential. Therefore, the study area spans three provinces with obvious differences in natural conditions (slope, rainfall, etc.) and socioeconomic activity intensity, enabling the implementation of different ecological protection measures according to various conditions to effectively improve regional carbon sink capacity.

3.3 Uncertainty Analysis

3.3.1 Data Uncertainty The land use data used in this study were derived from remote sensing image interpretation, a process that inherently involves some uncertainty. The data distinguished shrub forest from forestland and wetland from water bodies in type classification, but the carbon storage estimation required integration of the original nine land use types into six types, further increasing uncertainty in carbon storage estimation.

3.3.2 Model Uncertainty Regional carbon emissions were calculated using the emission coefficient method. Carbon emission coefficients for different land use types (cropland, forestland, grassland, water bodies, unused land, construction land) mainly referenced Sun He et al., whose study areas covered national scope or some southern cities (e.g., Wuxi, Wuhu), which still differ from actual environmental conditions in arid and semi-arid regions. Furthermore, when identifying driving factors of carbon storage, although multiple indicators reflecting regional natural conditions and socioeconomic activities were included, factors difficult to quantify such as ecological protection policies were not fully represented. Future research should further improve the comprehensiveness and accuracy of influencing factors.

4 Conclusions

From 1990 to 2023, the spatial distribution of land use types in the study area remained relatively stable, with grassland being the most important land use type, cropland and impervious surface areas increasing annually, and bare land area decreasing significantly. From 1990 to 2023, carbon emissions in the study area increased significantly, while carbon storage increased overall, with grassland showing the most prominent carbon storage capacity. The carbon balance index was much greater than 1, indicating that the study area functions as a carbon sink zone. Potential evapotranspiration is the primary driving factor affecting the regional carbon balance status, and the interactions among annual average precipitation, slope, potential evapotranspiration, and artificial forest area also significantly affect the regional carbon balance, indicating that the regional carbon balance status is jointly affected by natural and anthropogenic factors. By 2035, cropland area shows an expansion trend under all four scenarios, with forestland area increasing under the ecological protection scenario. Among the four simulation scenarios, only carbon emissions under the economic development scenario are higher than in 2023. Carbon storage increases under all four scenarios, with the cultivated land protection scenario showing the most significant increase, while the economic development scenario shows the smallest increase. The study results provide support for maintaining the important status of ecological protection barriers in arid and semi-arid regions and achieving low-carbon circular development.

References

Calvin K, Dasgupta D, Krinner G, et al. IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change[M]. Geneva, Switzerland. IPCC, 2023.

Liu X, Yang T, Wang Q, et al. Dynamics of soil carbon and nitrogen stocks after afforestation in arid and semi arid regions: A meta analysis[J]. Science of the Total Environment, 2018, 618: 1658-1667.

Liu Y, Fu B, Wang S, et al. Review and prospect of the water ecosystem nexus in dryland s Coupled Human Earth System[J]. Geographical Research, 2021, 40(2): 541-555.

Cheng Y, Luo P, Yang H, et al. Land use and cover change accelerated China s land carbon sinks limits soil carbon[J]. NPJ Climate and Atmospheric Science, 2024, 7(1): 199.

Qin Z, Zhu Y, Canadell J G, et al. Global spatially explicit carbon emissions from land use change over the past six decades (1961-2020)[J]. One Earth, 2024, 7(5): 835-847.

Huang H, Jia J, Chen D, et al. Evolution of spatial network structure for land use carbon emissions and carbon balance zoning in Jiangxi Province: A social network analysis perspective[J]. Ecological Indicators, 2024, 158: 111508.

Quan Y, Hutjes R W A, Biemans H, et al. Patterns and drivers of carbon stock change in ecological restoration regions: A case study of upper Yangtze River Basin, China[J]. Journal of Environmental Management, 2023, 348: 119376.

Wang X, Song J, Xiao Z, et al. Desertification in the Mu Us Sandy Land in China: Response to climate change and human activity from 2000 to 2020[J]. Geography and Sustainability, 2022, 3(2): 154-162.

Jiang W, Deng Y, Tang Z, et al. Modelling the potential impacts of urban ecosystem changes on carbon storage under different scenarios by linking the CLUE S and the InVEST models[J]. Ecological Modelling, 2017, 345(43): 30-40.

Li W, Jia S, He W, et al. Analysis of the consequences of land use changes and soil types on organic carbon storage in the Tarim River Basin from 2000 to 2020[J]. Agriculture, Ecosystems & Environment, 2022, 327: 107824.

Zhang R, Zhao X, Wang R, et al. Review of the effects of land use/cover change on soil organic carbon dynamic in arid and semi arid areas[J]. Chinese Journal of Ecology, 2024, 43(7): 2222-2230.

Zhou Y, Yan J, Liu J, et al. Spatio temporal variation in NEP in ecological zoning on the Loess Plateau and its driving factors from 2000 to 2021[J]. Environmental Science, 2024, 45(5): 2806-2816.

Guan Y, Wang J, Tan L, et al. Estimation of vegetation carbon source/sink and its response to land use change in the Loess Plateau, A case study of Yanhe River Basin[J]. Environmental Science, 2025, 46(3): 1657-1665.

Fan Q, Sun T, Zhang M, et al. Estimation and evolutionary analysis of carbon stocks in Shandong Province under the ecological cultivated land protection scenario[J]. Acta Ecologica Sinica, 2025, 45(4): 1588-1598.

Bi F, Wu Z, Liang H, et al. Spatiotemporal changes and driving factors of carbon storage in the middle reaches of the Yellow River based on the PLUS InVEST GeoDetector model[J]. Environmental Science, 2025, 46(8): 4742-4753.

Yang X, Liu X. Temporal and spatial differences in carbon conduction and prediction effect of land type transfer in Chang Tan Urban Agglomeration[J]. Environmental Science, 2022, 43(12): 5850-5860.

Ding Y, Wang L, Gui F, et al. Ecosystem carbon storage in Hangzhou Bay Area based on InVEST and PLUS models[J]. Environmental Science, 2023, 44(6): 3343-3352.

Zhao M, A G, Zhang J, et al. Ecological restoration impact on total terrestrial water storage[J]. Nature Sustainability, 2021, 4(1): 56-62.

Liu J, Pei X, Zhu W, et al. Multi budget balance in arid and semi arid regions scenario simulation of carbon[J]. Journal of Environmental Management, 2023, 346: 119016.

Wang J, Xu C. Geodetector: Principle and prospective[J]. Acta Geographica Sinica, 2017, 72(1): 116-134.

Liu J, Liu H, Zhuo Y, et al. Dynamics and driving forces of landscape patterns in Mu Us Sandy Land, from 1990 to 2014[J]. Pratacultural Science, 2017, 34(2): 255-263.

Jiang X, Gao S, Jiang Y, et al. Species diversity, functional diversity, and phylogenetic diversity in plant communities at different phases of vegetation restoration in the Mu Us sandy grassland[J]. Biodiversity Science, 2022, 30(5): 18-28.

Shi R, Wang J, Tan L, et al. Changes in NDVI and its multiscale spatiotemporal responses to precipitation in the Mu Us Desert[J]. Arid Zone Research, 2024, 41(8): 1395-1404.

Cao F, Zhou J, Xin Y, et al. Analysis of vegetation variation and driving mechanism in Mu Us Sandy Land under background of oasization[J]. Acta Ecologica Sinica, 2025, 45(9): 4431-4445.

Yang H, Wang H, Zuo H, et al. Change pattern and stability of oasisization land in Mu Us Sandy Land[J]. Chinese Journal of Applied Ecology, 2024, 35(3): 687-694.

Li J, Zhang F, Li Q, et al. Analysis and simulation of the spatial temporal evolution of carbon emission/storage of land use in Xinjiang based on InVEST model[J]. Journal of Agricultural Resources and Environment, 2025, 42(6): 1636-1647.

Fang X, Liu X, Yue D. Analysis of climate change characteristics and influencing factors in Mu Us Sandy Land from 1960 to 2018[J]. Research of Soil and Water Conservation, 2022, 29(2): 163-169.

Yu Q, Yu K, Zhang J. Comparative analysis of ecological changes based on photos taken in 1908 and 2019 in Mu Us Sandy Land[J]. Bulletin of Soil and Water Conservation, 2019, 39(6): 307-312.

Liang X, Guan Q, Clarke K C, et al. Understanding the drivers of sustainable land expansion using a patch generating land use simulation (PLUS) model: A case study in Wuhan, China[J]. Computers, Environment and Urban Systems, 2021, 85: 101569.

Hou J, Chen J, Zhang K, et al. Temporal and spatial variation characteristics of carbon storage in the source region of the Yellow River based on InVEST and GeoSoS FLUS models and its response to different future scenarios[J]. Environmental Science, 2022, 43(11): 5253-5262.

Sun Y, Mao D, Qiu D. Spatial and temporal analysis and multi scenario simulation of land use carbon emissions in Changsha City[J]. Journal of Agricultural Resources and Environment, 2025, 42(2): 529-542.

Sun H, Liang H. Land use patterns on carbon emission and spatial association in China[J]. Economic Geography, 2015, 35(3): 154-162.

Zhang Y, Liu C, He Z, et al. Research progress of hydrological process and soil organic carbon migration in slope field[J]. Chinese Journal of Soil Science, 2023, 54(3): 730-738.

Han X, Liu G, Xu H, et al. Spatial variation and scale effect of surface soil organic carbon content on typical slopes in the Loess Region, Ningxia[J]. Scientia Silvae Sinicae, 2024, 60(1): 19-31.

Liu X, Wang C, Gao J, et al. Approaches to carbon sequestration enhancement in China s plantation ecosystem for carbon peaking and carbon neutrality goals[J]. Acta Ecologica Sinica, 2023, 43(14): 5662-5673.

Xu L, Luo S, Guo C, et al. Carbon storage change in Xishuangbanna based on PLUS and InVEST model[J]. Ecology and Environmental Monitoring of Three Gorges, 2023, 8(2): 75-87.

Zhang X, Chen Y, Zhang Q, et al. Potential evapotranspiration determines changes in the carbon sequestration capacity of forest and grass ecosystems in Xinjiang, Northwest China[J]. Global Ecology and Conservation, 2023, 48: e02737.

Ru J, Wan S, Xia J, et al. Advanced precipitation peak offsets middle growing season drought in impacting grassland C sink[J]. New Phytologist, 2024, 244(5): 1775-1787.

Li S, Wang B, Wang Z, et al. Spatiotemporal changes and driving forces of carbon storage in agricultural interlacing zone of Greater Khingan Mountains using PLUS InVEST model[J]. Transactions of the Chinese Society of Agricultural Engineering, 2024, 40(21): 232-241.

Liu Y, Guo W, Liao D, et al. Restoration of soil mineral particle bound inorganic carbon sequestration effect by sand fixing forest in Mu Us Sandy Land[J]. Journal of Soil and Water Conservation, 2025, 39(4): 31-38, 47.

Ma J, Tong X, Li Z, et al. Carbon sequestration in soil particle sized fractions during reversion of desertification at Mu Us Sand Land[J]. Chinese Journal of Applied Ecology, 2016, 27(11): 3487-3494.

Shi R. Distribution and Influencing Factors of SOC Active Fractions in the Transitional Zone of Loess Plateau and Mu Us Sandy Land[D]. Yangling: Northwest A & F University, 2025.

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

Source: ChinaXiv —Machine translation. Verify with original.