Carbon Storage Change and Spatial Pattern in the Mata Watershed from 1999 to 2016 Based on the InVEST Model: A Postprint

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Abstract

Regional carbon storage serves as a crucial metric for ecosystem functioning, and investigating the impacts of land transformation on regional carbon storage dynamics is of significant importance for harmonizing regional ecological construction with ecological industry development. Employing the InVEST model and Geographic Information System (GIS) technology, this study quantified changes in regional carbon storage during land structural transformation in the Mata Watershed, southern Yan' an, Shaanxi Province, from 1999 to 2016, and explored the influence of slope gradient, aspect, and position on the spatial distribution of carbon storage. The results indicate that the 18-year land transformation in the Mata Watershed increased regional carbon storage by 1688.36 Mg (carbon density increased by 6.92 $\mathrm{Mg \cdot hm^{-2}}$), representing an enhancement of approximately 7.63% in total carbon sequestration function. The expansion of forest, grassland, and orchard land types constituted the primary contributors to increased watershed landscape carbon storage following vegetation conversion. Spatially, carbon storage gains were predominantly located on semi-shady slopes, upper-middle slope positions, and gradients ranging from 10° to 30°. This study demonstrates that both forest and grassland vegetation restoration and economic fruit forest establishment enhance the carbon sequestration capacity of the Mata Watershed landscape. The land conversion model implemented in the Mata Watershed effectively coordinates regional ecological construction and ecological industry development, offering valuable applicability for promotion in the Loess Hilly Region.

Full Text

Preamble

Study on change in carbon storage and its spatial pattern in Mata Watershed from 1999 to 2016 based on InVEST model

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Abstract

Regional carbon storage serves as a crucial metric for ecosystem function, and exploring the impacts of land transformation on carbon storage dynamics is essential for coordinating regional ecological construction with eco-industrial development. This study employed the InVEST model integrated with GIS technology to investigate carbon storage changes in the Mata Watershed of southern Yan' an, Shaanxi Province, during land structure transformation from 1999 to 2016, and examined how slope, aspect, and slope position influence the spatial distribution of carbon storage. The results demonstrated that land transformation in the Mata Watershed increased regional carbon storage by 1688.36 Mg (carbon density increased by 6.92 $\mathrm{Mg \cdot hm^{-2}}$), enhancing total carbon sequestration capacity by approximately 7.63%. The expansion of forest, grassland, and orchard land types emerged as the primary contributors to enhanced watershed landscape carbon storage following vegetation conversion. Spatially, carbon storage gains were predominantly located on semi-shaded slopes, upper and middle slope positions, and slopes ranging from 10° to 30°. This study concludes that both forest/grass vegetation construction and economic orchard development benefit carbon sequestration in the Mata Watershed, and the land conversion model employed here can effectively coordinate ecological construction with industrial development, offering valuable insights for the Loess Hilly Region.

Keywords: carbon storage; spatial pattern; InVEST model; ecosystem services; Mata Watershed

1. Introduction

Carbon sequestration represents one of the most vital ecosystem services, playing a critical role in reducing atmospheric greenhouse gas concentrations, regulating regional microclimates, mitigating global climate change, and maintaining ecological balance. In recent years, research on ecosystem carbon storage and spatial patterns has become a focal point for governments and scientists worldwide, providing essential reference value for natural resource management and ecological decision-making.

Current carbon storage estimation methods vary across scales. Small-to-medium scale assessments typically employ field surveys, instrumental measurements, and statistical methods, which are time-consuming, labor-intensive, and yield static results that cannot accurately reflect dynamic changes or spatial patterns. Large-scale estimates generally rely on model-based approaches. The InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) model, developed jointly by Stanford University, The Nature Conservancy, and the World Wildlife Fund, offers an open-source tool for quantifying multiple ecosystem services. By integrating natural capital into decision-making processes, it enables rapid, straightforward, and accurate estimation of regional carbon storage and its spatial dynamics, visualized through maps. The model has been widely applied across diverse regions, including the United States, India, Tanzania, China' s Wenchuan earthquake zone, the middle-lower Yangtze Plain, Beijing mountainous areas, and the Qilian Mountains.

The Loess Hilly Region of China suffers from severe soil erosion and fragile ecological conditions. Since the 1970s, soil conservation projects and the subsequent Grain-for-Green Program (initiated in 1999) have substantially increased vegetation coverage. While numerous studies have examined vegetation carbon sequestration benefits from these initiatives, most have focused on soil conservation and afforestation effects. However, under current policies promoting new rural construction and ecological agriculture, land use patterns have shifted significantly, with traditional soil conservation forests being replaced by economic forests like apple orchards (Malus pumila), particularly around Yan' an. Quantifying how economic orchard construction affects regional carbon sequestration capacity has become an urgent scientific question.

This study selects the Mata Watershed—a typical representative of the Loess Hilly Region—as an ideal case study. From 1999 to 2016, apple orchard area in this watershed increased continuously, providing an excellent opportunity to examine how changing vegetation restoration patterns affect regional carbon sequestration. The watershed, covering 2.4 km^2 with elevations ranging from 1185 to 1379 m, features a typical loess hilly landscape with semi-arid climate (annual precipitation 544 mm, mean temperature 8.8°C). The dominant soil type is loessal soil, and the primary industry is dryland apple cultivation, serving as the local economic pillar. Using the InVEST model, this research evaluates carbon sequestration capacity and its spatial allocation characteristics from 1999 to 2016, aiming to provide scientific guidance for sustainable vegetation construction and eco-industrial development in the Loess Hilly Region.

2. Methods

2.1 Study Area

The Mata Watershed (109.5268°N, 36.4695°E) is located in southern Baota District, Yan' an City, Shaanxi Province, covering a typical loess hilly area of 2.4 km^2. The region experiences a semi-arid climate with cold, dry winters, concentrated summer precipitation, and potential evapotranspiration exceeding rainfall. Annual average temperature is approximately 8.8°C, with mean annual precipitation of 544 mm. The dominant soil type is loessal soil, and dryland apple cultivation forms the backbone of the local economy.

2.2 Land Use Data Sources

Land use maps for 1999 and 2016 were derived from Landsat remote sensing data. For the 2016 map, Landsat 8 imagery was selected using bands 2, 3, 4, 5, 6, and 7; for the 1999 map, Landsat 7 imagery utilized bands 1, 2, 3, 4, 5, and 7. All imagery underwent topographic correction, radiometric calibration, and atmospheric correction to convert digital numbers to surface reflectance. The 2016 land use map was generated through supervised classification (Random Forest algorithm) using field survey data and processed Landsat 8 imagery, achieving a prediction accuracy of 90.66% and Kappa coefficient of 0.88. The trained Random Forest model was then applied to 1999 Landsat 7 imagery to produce the historical land use map. Land use was classified into six categories: forest, shrubland, grassland, orchard, cropland, and other (roads, villages, water bodies).

The land use transition matrix revealed that forest primarily converted to shrubland, grassland, and orchard; shrubland mainly converted to grassland and orchard; while grassland, cropland, and other lands predominantly converted to orchard. Among all land use types, forest, grassland, and orchard showed net area increases, whereas shrubland, cropland, and other lands exhibited net decreases. Notably, orchard area expanded most dramatically, increasing from 34.7% of total watershed area in 1999 to 47.4% in 2016.

2.3 Carbon Storage Estimation

Terrestrial ecosystem carbon storage comprises four components: aboveground biomass carbon (C_{above}), belowground biomass carbon (C_{below}), soil carbon (C_{soil}), and dead organic carbon (C_{dead}). C_{above} includes carbon in all living vegetation components (branches, stems, leaves); C_{below} represents carbon in live roots; C_{soil} encompasses carbon in mineral and organic soils; and C_{dead} includes carbon in dead vegetation and litter. Total carbon storage is calculated as:

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

This study employed InVEST 3.4.0 for carbon storage estimation. Model parameters (carbon densities) were obtained from literature review and are summarized in Table 2.

2.4 Terrain Factor Analysis

Slope, aspect, and slope position represent key topographic indicators. In the Mata Watershed, slopes range from 0° to 36.63°. For analysis, slopes were categorized into eight classes: 0°-5°, 5°-10°, 10°-15°, 15°-20°, 20°-25°, 25°-30°, and >30°. Aspect was classified based on solar illumination intensity into shaded slopes (0°-45°, 225°-270°), semi-shaded slopes (45°-90°, 270°-315°), semi-sunny slopes (90°-135°, 315°-360°), and sunny slopes (135°-225°). Elevation ranges from 1185 to 1379 m, divided into three equal intervals representing lower (1185-1250 m), middle (1250-1315 m), and upper (1315-1379 m) slope positions. ArcMap 10.6 raster analysis tools were used to generate spatial carbon storage maps and analyze terrain factor effects.

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3. Results

3.1 Spatial Patterns and Temporal Changes in Watershed Carbon Storage

Total ecosystem carbon storage in the Mata Watershed increased from 22,120.25 Mg in 1999 (carbon density 90.66 $\mathrm{Mg \cdot hm^{-2}}$) to 23,808.61 Mg in 2016 (carbon density 97.58 $\mathrm{Mg \cdot hm^{-2}}$), representing a net increase of 1,688.36 Mg (carbon density increase of 6.92 $\mathrm{Mg \cdot hm^{-2}}$) and a 7.63% enhancement in carbon sequestration capacity. Carbon storage gains were concentrated primarily in the southern portion of the watershed.

3.2 Carbon Storage Dynamics by Land Use Type

Land use transitions between 1999 and 2016 caused substantial changes in carbon storage across land use types (Figure 3). Forest, grassland, and orchard carbon storage increased, while shrubland, cropland, and other lands decreased. The overall carbon storage increase across all land use types was 7,484.62 Mg, with forest contributing 42.57% of the total increase, orchard 39.71%, and grassland 17.72%. Conversely, carbon storage reductions totaled 5,796.27 Mg, with shrubland accounting for 76.01% of the total decrease. These results indicate that forest, grassland, and orchard expansion served as the primary drivers of enhanced watershed carbon storage.

3.3 Effects of Terrain Factors on Carbon Storage

Analysis across eight slope gradient classes revealed that watershed carbon storage was predominantly distributed on slopes of 10°-30°, which accounted for approximately 96.78% of total watershed carbon storage, with the 15°-20° slope class showing the highest carbon storage. The most significant carbon storage increases occurred on 10°-30° slopes, which contributed 70.71% of total carbon storage gains, whereas gentler slopes (0°–5°) showed minimal change or slight decreases.

Carbon storage distribution across slope positions indicated that lower and middle slope positions contained the majority of watershed carbon storage, with upper slopes holding smaller proportions. Between 1999 and 2016, carbon storage increases primarily occurred on middle and upper slope positions (increasing by 2,354.07 Mg), while lower slope positions experienced decreases (declining by 1,688.36 Mg), demonstrating that middle and upper slope positions were the main topographic contributors to carbon storage growth.

Aspect analysis showed that carbon storage gains were concentrated on semi-shaded slopes, which contributed 70.71% of total carbon storage enhancement, while other aspects showed minimal change or stability (e.g., sunny slopes). This pattern indicates that semi-shaded slopes represent the primary topographic setting for land use conversion and carbon sequestration enhancement.

4. Discussion

4.1 Carbon Storage Changes and Policy Implications (1999-2016)

This study quantified carbon storage capacity and its spatial allocation in the Mata Watershed following land use conversion from 1999 to 2016 using the InVEST model. Results demonstrate that 18 years of land use transformation (primarily orchard expansion) enhanced watershed carbon sequestration capacity by approximately 7.63%. The conversion of cropland, shrubland, and bare land to forest, grassland, and orchard land use types directly drove landscape carbon storage increases, particularly through forest expansion in upstream areas and orchard development in midstream and downstream regions.

The primary socioeconomic drivers were the national Grain-for-Green policy and recent ecological agriculture initiatives. During vegetation restoration, extensive areas of cropland, shrubland, and bare land were converted to forest, grassland, and orchard. While previous research on the Loess Plateau has documented carbon benefits from afforestation programs, few studies have addressed the carbon sequestration impacts of orchard development. This research reveals that orchard land represents a major contributor to landscape carbon storage enhancement, a finding largely overlooked in previous assessments of the Grain-for-Green Program’ s carbon benefits.

Under current policies promoting new rural construction and ecological agriculture, conversion of soil conservation forests and cropland to orchard land has accelerated around Yan’ an. The Mata Watershed case study demonstrates that orchard policies yield similar carbon benefits to afforestation policies, enhancing regional carbon sequestration capacity. Although orchards exhibit weaker carbon sequestration than conservation forests, their capacity exceeds that of cropland, grassland, and shrubland. The conversion of former cropland, grassland,

and shrubland to orchard land explains the observed carbon storage increase.

Beyond ecological benefits, the economic returns from orchards cannot be ignored. Ensuring farmer income is crucial for the long-term sustainability of soil conservation and ecological restoration projects. Dryland apple cultivation has become the pillar industry for Mata Watershed residents. Recent poverty alleviation policies and government support for apple cultivation have established comprehensive institutional frameworks, driving continuous orchard expansion. The integrated optimization and allocation of economic forest areas will shape future trends in soil conservation and economic development in the Loess Hilly Region, representing a distinctive feature of future development on the Loess Plateau. However, enhancing the carbon sequestration benefits of economic forests to match those of conservation forests remains an important research priority for maximizing both ecological and economic benefits.

4.2 Uncertainty Analysis and Practical Significance

This assessment of carbon storage dynamics in the Mata Watershed from 1999 to 2016 relies on the InVEST model, which assumes constant carbon densities for ecosystem components over time. However, as vegetation grows, carbon densities may continue increasing. Additionally, the model does not account for management practices in cropland and orchard that could enhance carbon sequestration potential. Therefore, using fixed carbon density values may underestimate the watershed’ s carbon storage potential.

While this study cannot provide precise carbon storage estimates, it effectively captures the directional trend of carbon storage changes following land use conversion and identifies spatial hotspots of carbon accumulation. This information helps locate areas of carbon storage increase and informs effective land use conversion strategies. For instance, carbon storage gains were concentrated on semi-shaded slopes, middle and upper slope positions, and 10°-30° slopes—areas where land use conversion to forest or orchard proved particularly effective. The 2016 land use map confirms these topographic positions are dominated by orchards (primarily apple), indicating that converting former cropland, grassland, and shrubland to orchard was the main driver of watershed carbon storage enhancement.

The average carbon density of the Mata Watershed (97.58 $\mathrm{Mg \cdot hm^{-2}}$) is lower than that of more humid regions such as the Xijiang River Basin in Guangxi (186.99 $\mathrm{Mg \cdot hm^{-2}}$), Qilong County in Guizhou (173.1 $\mathrm{Mg \cdot hm^{-2}}$), the Qihe River Basin in the Taihang Mountains, and Huanghua in Hebei, reflecting the relatively lower potential carbon sequestration capacity of arid and semi-arid ecosystems.

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5. Conclusions

1) Over the past 18 years of vegetation structural transformation in the Mata Watershed (primarily apple orchard expansion), total regional carbon storage increased by 7.63%. The dramatic expansion of forest, grassland, and orchard areas directly caused this carbon storage increase, with orchards contributing 39.71% of the total enhancement.
2) Both orchard development and afforestation policies produce similar carbon benefits for the Mata Watershed, enhancing regional landscape carbon sequestration capacity.
3) Carbon storage gains were concentrated on semi-shaded slopes, middle and upper slope positions, and slopes of 10°-30°, indicating that land use conversion strategies targeting these topographic positions (conversion to forest or orchard) have strong potential for broader application.
4) The continued expansion and integrated optimization of economic forests will shape future trends in soil conservation and economic development in the Loess Hilly Region. Enhancing the carbon sequestration benefits of economic forests to approach those of conservation forests will maximize both ecological and economic benefits in the region.

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