Differences in Carbon Sequestration Capacity and Driving Forces between Native and Restored Grasslands in China: Postprint

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Abstract

Net Primary Production (NPP) is an important indicator that reflects grassland growth conditions and characterizes grassland carbon sequestration capacity. This study takes four northern provinces of China as the research area, and based on multi-source remote sensing data such as NPP and land cover, as well as statistical data on society, economy, and meteorology, analyzes the spatiotemporal variation and key driving forces of carbon sequestration capacity in native and restored grasslands, providing a reference for formulating more targeted grassland ecological policies in China. The results show that the carbon sequestration capacity of restored grasslands is approximately 80% higher than that of native grasslands; the spatial clustering of carbon sequestration capacity in native grasslands (0.534~0.653) is slightly narrower than that in restored grasslands (0.511~0.736); rainfall, sunshine duration, and ecological protection zone policies are common driving forces for enhancing grassland carbon sequestration, with rainfall reaching 600 mm and annual sunshine duration exceeding 3000 h providing the optimal enhancement of grassland carbon sequestration; temperatures exceeding 8 ℃ are beneficial for carbon sequestration in native grasslands, and the optimal area for restored grasslands ranges between 100~200 km2; before the implementation of ecological restoration policies by the government, meteorological conditions were the main driving force for grassland restoration, with the influence of policies gradually increasing after implementation; relevant departments should continue to promote effective ecological restoration policies to help China achieve its "dual carbon" goals at an early date.

Full Text

Abstract

Net primary productivity (NPP) is a crucial indicator that reflects grassland growth conditions and characterizes grassland carbon sequestration capacity. This study examines four northern Chinese provinces as the research area, analyzing spatiotemporal variations in carbon sequestration capacity between primary and restored grasslands and identifying key driving forces based on multisource remote sensing data (including NPP and land cover) alongside socioeconomic and meteorological statistics. The findings provide scientific references for formulating more targeted grassland ecological policies in China. Results indicate that the carbon sequestration capacity of restored grasslands is approximately 80% higher than that of primary grasslands. The spatial aggregation range of primary grassland carbon sequestration capacity (0.534–0.653) is slightly narrower than that of restored grasslands (0.511–0.736). Rainfall, sunshine duration, and ecological conservation zone policies constitute common driving forces for enhancing grassland carbon sequestration, with optimal enhancement occurring when rainfall reaches 600 mm and annual sunshine duration exceeds 3000 h. Temperatures above 8°C favor carbon sequestration in primary grasslands, while the optimal restoration area for restored grasslands ranges between 100–200 km^2. Prior to policy implementation, meteorological conditions served as the primary driver of grassland restoration, though policy influence gradually strengthened thereafter. Relevant authorities should continue advancing effective ecological restoration policies to support China’ s “dual carbon” goals.

Keywords: arid regions; primary grasslands; restored grasslands; carbon sequestration capability; random forest

Introduction

Grasslands constitute a vital ecological security barrier in China, covering approximately 40% of the country’ s total land area. Predominantly distributed across arid and semi-arid regions, these ecosystems provide essential livelihood support for local residents while delivering critical ecological, economic, social, and cultural services to society at large. Existing research systematically analyzes grassland carbon sequestration capacity through net primary productivity (NPP) measurement, spatiotemporal variation characterization, and driver identification, providing robust theoretical support for understanding dynamic evolution patterns. However, over the past 50 years, more than 90% of China’ s grasslands have experienced varying degrees of degradation due to human activities and climate change—a proportion significantly higher than the less than 20% observed in Europe and North America. This degradation directly impacts local livestock development, threatens pastoral livelihoods, and substantially weakens grassland carbon sequestration capacity.

To mitigate overexploitation and enhance ecosystem stability, China has implemented comprehensive grassland restoration projects, including the "Grazing Withdrawal and Grassland Restoration" program, the Three-River-Source National Nature Reserve, and the Wuliangsuhai watershed ecological restoration pilot project. These initiatives demonstrate greater systematic integration than comparable international policies, simultaneously expanding grassland area, enhancing carbon sequestration capacity, and promoting sustainable local economic development to achieve ecological-economic synergies.

Despite these efforts, research gaps persist. Current studies lack systematic comparisons of carbon sequestration effects between primary grasslands (natural grasslands without land-use change) and restored grasslands (converted from barren land, cropland, or urban areas), particularly regarding long-term sequestration capacity. Although machine learning models like random forest have been employed to assess grassland carbon sequestration, existing research fails to differentiate between grassland types in terms of carbon capacity, biodiversity, and soil hydrological characteristics. Furthermore, while studies cover extensive temporal and spatial scales, they inadequately account for complex non-linear relationships and interactions among factors, limiting scientific support for location-specific, differentiated management strategies.

This study addresses these gaps by examining four northern provinces in China' s arid and semi-arid regions, using remote sensing data to measure NPP spatiotemporal dynamics and applying random forest machine learning to identify key influencing factors and their non-linear responses for both grassland types. The findings enrich current understanding of grassland carbon sequestration and provide scientific references for China' s "dual carbon" objectives and sustainable grassland development strategies.

1.1 Study Area Overview

China exhibits complex climate patterns, with drought in the north and humidity in the south, and terrain that rises from east to west. This geographic heterogeneity creates significant differences in ecological environments and natural resource distribution. Grassland resources are concentrated primarily in Inner Mongolia, Xinjiang, Gansu, and Ningxia—northern provinces that collectively account for approximately 80% of China' s total grassland area and represent crucial natural resources for local ecological balance and economic development.

However, decades of overgrazing and expanding human activities have caused severe degradation and desertification, affecting over 70% of grasslands in these regions and threatening regional ecological balance and sustainable development capacity. To address this crisis, China launched the "Grazing Withdrawal and Grassland Restoration" program in January 2003 across northern provinces, targeting important ecological zones, severely water-eroded areas, and desertification-prone cultivated lands for grassland restoration. The program implemented grazing bans, rotational grazing, and seasonal grazing restrictions to protect grassland growth and reproduction and enhance productivity. By the program' s conclusion, national investment totaled 2.4×10^{11} RMB, effectively curbing degradation trends and improving carbon sequestration capacity.

This study focuses on Xinjiang Uygur Autonomous Region, Inner Mongolia Autonomous Region, Ningxia Hui Autonomous Region, and Gansu Province (Fig. 1), covering approximately 3.35×10^{6} km^2 (35% of China's total area). According to agricultural climate zoning classifications, this region experiences arid to semi-arid continental climate, with mean annual temperatures ranging from -4.8 to 15.9°C, annual sunshine duration exceeding 2500 hours, and mean annual precipitation below 400 mm.

[Figure 1: see original paper]

1.2 Data Sources and Processing

1.2.1 Land Use Data and Classification of Primary and Restored Grasslands

Land use data were obtained from the China Land Cover Dataset (CLCD) at 30 m × 30 m spatial resolution for 2001–2020. Using ArcMap software, we identified, extracted, and calculated grassland area and spatial distribution. The extracted grassland coverage closely approximated statistics published by the State Forestry Administration, validating data reliability.

Given that grassland carbon sequestration is influenced by socioeconomic development, climate, and policies, multiple land conversion scenarios occur simultaneously (forest-to-grassland, barren-to-grassland, cropland-to-grassland, urban-to-grassland). This study focused on restored grasslands transitioning from low-NPP to high-NPP states. We identified grassland types by comparing pixel changes between consecutive years: pixels that were barren land, cropland, or urban areas in year *t-1* and became grassland in year *t* were classified as restored grasslands, while pixels remaining grassland in both years were classified as primary grasslands. Missing values and outliers were marked and cross-referenced with the China Multi-Period Land Use Remote Sensing Monitoring Dataset, using surrounding land use types to infer pixel classifications. Pixels with large discrepancies were retained as missing values to avoid bias.

1.2.2 Grassland Net Primary Productivity Data

NPP data were derived from the MODIS MOD17A2H product (2001–2020) at 500 m × 500 m spatial resolution. We overlaid NPP data with land use data to extract grassland NPP values and calculated average NPP per pixel (ANPP). County-scale grassland NPP data were then computed using national county-level administrative boundary maps. Missing values and outliers were identified by comparing surrounding pixel values; significant discrepancies were retained as missing values or removed to minimize impacts on average NPP calculations.

1.2.3 Digital Elevation Model Data

The Digital Elevation Model (DEM) provides digital representation of terrain topography, including elevation, slope, and aspect information. This study used the national DEM dataset from the Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, derived from Shuttle Radar Topography Mission (SRTM) data at 90 m$×$90 m resolution. The data were resampled and clipped according to grassland locations to obtain elevation information for grassland pixels in the four provinces, ultimately calculating county-scale average elevation.

1.2.4 Socioeconomic and Meteorological Data

County-level socioeconomic and meteorological data were obtained from statistical yearbooks and China County Economic Yearbooks during the study period. Socioeconomic variables included per capita GDP, grain yield, urban area, cultivated land area, year-end population, local fiscal budget expenditure, and animal husbandry added value—factors considered influential for NPP changes and grassland restoration. Meteorological data (precipitation, sunshine duration, temperature) were acquired from the China Meteorological Data Sharing Service System for 98 meteorological stations. Each county was spatially linked to its nearest meteorological station; counties without stations used spatial interpolation, a method proven effective for reflecting China’ s climate characteristics in ecological research.

1.3 Methods

1.3.1 Temporal Change Measurement

We analyzed NPP trends by extracting annual NPP values for each grid cell and calculating county-level averages. The temporal change rate was computed as:

$$Q_{it} = \frac{Q_{it} - Q_{i(t-1)}}{Q_{i(t-1)}} \times 100\%$$

where Q_{it} represents county i’ s grassland NPP in year t, and $Q_{i(t-1)}$ is the previous year’ s NPP. Descriptive analysis characterized temporal dynamics of grassland NPP enhancement.

1.3.2 Spatial Aggregation Measurement

Global spatial autocorrelation (Global Moran’ s I) measured spatial clustering of NPP across the four provinces:

$$I = \frac{n}{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}} \times \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(x_i - \bar{X})(x_j - \bar{X})}{\sum_{i=1}^{n}(x_i - \bar{X})^2}$$

where I is the Global Moran' s I index, n is the number of sample counties, x_i and x_j represent NPP values in counties i and j, w_{ij} is the spatial weight matrix (adjacent counties = 1, non-adjacent = 0), and $\bar{X}$ is the mean NPP. Positive values indicate spatial clustering, while negative values indicate dispersion. All years were significant at the $p < 0.001$ level.

Local spatial autocorrelation was analyzed using the Getis-Ord G_i^* index to identify hotspot locations:

$$G_i^* = \frac{\sum_{j=1}^{n} w_{ij}x_j - \bar{X}\sum_{j=1}^{n} w_{ij}}{S\sqrt{\frac{n\sum_{j=1}^{n} w_{ij}^2 - (\sum_{j=1}^{n} w_{ij})^2}{n-1}}}$$

This index detects local spatial clustering of high and low NPP values, enabling visualization of spatial patterns.

1.3.3 Random Forest Machine Learning Model

The random forest model, proposed by Breiman (2001), is a classifier that trains on existing samples and makes predictions. Compared to other algorithms, it handles large-scale data accurately, maintains robustness in decision-making, avoids multicollinearity issues, prevents overfitting, and offers strong predictive capability.

Variable importance was assessed using two metrics: %IncMSE (mean decrease in model accuracy when variables are permuted) and IncNodePurity (mean decrease in node impurity). The model was constructed with 500 decision trees (ntree = 500) and default parameters, using 70% of data for training and 30% for testing.

We selected 15 key variables as input factors: population, GDP, fiscal budget expenditure, animal husbandry added value, grain yield, annual precipitation, sunshine duration, temperature, grassland area, urban area, cultivated land area, elevation, new grassland area, and ecological restoration policy (grazing withdrawal). These factors were considered potentially influential for grassland carbon sequestration potential.

2 Results and Analysis

2.1 Temporal Variation of Grassland Carbon Sequestration Capacity

Analysis of annual average NPP for primary and restored grasslands from 2001–2020 revealed that primary grassland NPP was consistently lower than restored grassland NPP, likely because restored grasslands received greater protection and faced lower risks of destructive development from grazing and tourism. Primary grassland NPP increased by approximately 113 g $C \cdot m^{-2}$ from 2001-2020, though its growth rate declined. Restored grassland NPP showed substantial increases before 2015, rising from 366.89 to 456.74 g $C \cdot m^{-2}$, followed by a slight decline of about 24 g $C \cdot m^{-2}$, then resumed growth after 2018, surpassing 2015 levels. Although both grassland types exhibited fluctuations, the overall trend was upward, indicating positive effects from restoration policies.

[Figure 2: see original paper]

2.2 Spatial Patterns of Grassland Carbon Sequestration

2.2.1 Overall Spatial Patterns Global Moran' s I analysis revealed significant spatial clustering for both grassland types across all years (Table 2). Primary grassland NPP showed Moran' s I values ranging from 0.534-0.653, while restored grasslands ranged from 0.511-0.736, indicating strong spatial autocorrelation and substantial inter-county influence. This suggests that coordinated administrative strategies are essential for effective grassland protection.

2.2.2 Local Spatial Patterns Local Getis-Ord G_i^* analysis identified spatial hotspots and coldspots (Fig. 3). Primary grassland hotspots expanded gradually over time, particularly in southwestern Xinjiang, demonstrating positive radiative effects as the grazing withdrawal policy deepened. Restored grassland hotspots initially decreased then increased, with clustering also concentrated in southern Xinjiang. Coldspot analysis revealed diminishing low-value clusters in southern Inner Mongolia for primary grasslands, while restored grassland coldspots showed complex patterns without significant expansion of negative radiative effects.

[Figure 3: see original paper]

2.3 Driving Forces of Grassland Carbon Sequestration Enhancement

2.3.1 Model Applicability Assessment Comparing random forest and multiple linear regression models, random forest achieved higher training set R^2 values, demonstrating superior capability in analyzing complex non-linear relationships and interactions affecting grassland carbon sequestration capacity.

2.3.2 Identification and Analysis of Driving Forces Variable importance ranking (Fig. 4) revealed that for primary grasslands, annual precipitation ranked highest, followed by primary grassland area, urban area, cultivated land area, and grain yield. For restored grasslands, grazing withdrawal policy status, restored grassland area, annual precipitation, sunshine duration, and fiscal budget were most important. Meteorological factors remained dominant drivers for both types, though policy factors showed significant positive effects, particularly for restored grasslands.

[Figure 4: see original paper]

Partial dependence plots visualized marginal effects of key drivers (Figs. 5-6). For primary grasslands, NPP increased with precipitation up to 600 mm, then plateaued; sunshine duration effects peaked at 3000 h; temperature effects became positive above 8°C. For restored grasslands, precipitation effects accelerated after 600 mm; sunshine duration showed continuous positive effects up to 3000 h; restoration area effects peaked at 100-200 km^2, suggesting optimal management scales.

[Figure 5: see original paper] [Figure 6: see original paper]

2.3.3 Temporal Evolution of Key Driving Forces Analyzing three policy periods—pre-grazing withdrawal (2001-2002), policy implementation (2003-2010), and ecological conservation subsidy period (2011-2020)—revealed shifting driver importance (Table 3). Before 2003, climate factors dominated for both grassland types. During policy implementation (2003-2010), policy factors and grassland area became increasingly important, particularly for restored grasslands. During the subsidy period (2011-2020), policy and climate factors remained primary drivers, with socioeconomic factors showing limited influence on primary grasslands but growing impact on restored grasslands.

3 Discussion

3.1 Restored Grasslands Demonstrate Greater Carbon Sequestration Potential

Restored grasslands exhibited approximately 80% higher carbon sequestration capacity than primary grasslands, with more pronounced improvement over time. This suggests that active management promotes rapid soil nutrient uptake, optimizes species composition, and reduces external negative impacts. Spatial hotspot analysis identified two distinct regions: high-capacity clustering in southern Xinjiang and low-capacity clustering in southern Inner Mongolia and parts of Ningxia. Over time, hotspot areas expanded while coldspot areas diminished and dispersed, indicating effective restoration measures in northern China' s arid and semi-arid regions.

3.2 Meteorological and Policy Drivers Show Greatest Impact

Random forest analysis identified precipitation, sunshine duration, and grazing withdrawal policy as common key drivers for both grassland types, consistent with existing research. Optimal conditions (precipitation >600 mm, sunshine >3000 h) significantly enhance carbon sequestration. Temperatures above 8°C favor primary grassland recovery through natural growth, while restored grasslands benefit from both favorable climate and human management. Restoration areas of 100-200 km^2 enable more effective management and carbon sequestration gains.

3.3 Divergent Drivers Across Time Periods

Primary and restored grasslands showed differentiated driver rankings across periods, likely due to varying intervention intensity, human disturbance levels, and natural environmental changes. Before 2003, climate factors dominated. During 2003-2010, policy impacts emerged, with grassland area significantly affecting restored grasslands. During 2011-2020, policy and climate remained key drivers, though socioeconomic factors gained importance for restored grasslands.

3.4 Meteorological Monitoring and Policy Deepening as Critical Measures

Management agencies should deepen ecological restoration policies, increase funding and infrastructure, and improve management efficiency. Meteorological departments should enhance climate monitoring and intervention to maintain optimal growth conditions. Local governments must consider grassland restoration area scales, avoiding overly large projects that compromise management effectiveness.

4 Conclusion

Long-term observations reveal upward trends in carbon sequestration capacity for both grassland types, with restored grasslands outperforming primary grasslands. Meteorological and policy factors constitute the two core drivers of grassland carbon sequestration recovery. Authorities should continue optimizing ecological restoration policies while actively managing meteorological factors to accelerate carbon sequestration recovery and achieve significant ecological benefits. Restoration area scales require careful consideration to avoid management inefficiencies.

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