Spatiotemporal Evolution Characteristics and Influencing Factors of GPP in China's Drylands: A Postprint

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Date: 2024-07-04T00:00:00+00:00

Abstract

To elucidate the carbon sequestration capacity of ecosystems in China's arid regions and its underlying change mechanisms, this study delineated the extent of China's arid regions based on the AI index and investigated the spatiotemporal evolution characteristics and driving factors of vegetation carbon sequestration capacity in these regions from 2001 to 2020. This was accomplished by utilizing MODIS gross primary productivity (GPP) datasets in conjunction with meteorological data including temperature, precipitation, vapor pressure deficit (VPD), and soil water content, as well as human activity data such as land use. The results indicate: (1) GPP in China's arid regions showed an increasing trend during the 20-year period, with 64.72% of the area exhibiting a statistically significant increasing trend; (2) Temperature had the lowest influence on GPP, with a relative contribution rate of 21.70%, whereas precipitation and soil water content were the dominant drivers of GPP increase, with their combined contributions exceeding 55%. As aridity intensified, water stress effects gradually strengthened. Across different vegetation types, precipitation was the most important climatic factor affecting GPP variation in all types except mixed forests and alpine vegetation; (3) Variations in soil type and geomorphological type were the primary factors controlling the spatial differentiation of GPP, while water availability and land use type also played significant roles. The explanatory power of interactions between any two factors surpassed that of individual factors, with interactions between soil type and other factors being the most pronounced. These findings hold important theoretical significance for advancing our understanding of carbon sink evolution characteristics in China's arid ecosystems and their response mechanisms to environmental factors.

Full Text

Characteristics of Spatiotemporal Evolution of Gross Primary Productivity and Its Influencing Factors in China's Drylands

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Abstract

To clarify the carbon sequestration capacity and its change mechanisms in China's dryland ecosystems, this study delineated the extent of China's drylands based on the aridity index (AI) and investigated the spatiotemporal evolution characteristics of vegetation carbon sequestration capacity in China's drylands from 2001 to 2020 using the MODIS Gross Primary Productivity (GPP) dataset. Combined with meteorological data including temperature, precipitation, vapor pressure deficit (VPD), soil water content, and human activities such as land use, the influencing factors were analyzed. The results show that: (1) Over the 20-year period, GPP in China's drylands exhibited an increasing trend, with 64.72% of the region showing a significant increase. (2) Temperature had the lowest impact on GPP, with a relative contribution rate of 21.70%. Precipitation and soil water content were the dominant factors driving GPP growth, with their combined contribution rate exceeding 55%. As drought intensity increased, the effect of water stress gradually strengthened. Among different vegetation types, except for mixed forests and alpine vegetation, precipitation was the most important climate factor affecting GPP changes. (3) Differences in soil type and landform type were the dominant factors influencing the spatial variation of GPP. Moisture conditions and land use type also played important roles, with the explanatory power of interactions between any two factors exceeding that of single factors. The interaction between soil type and other factors was particularly significant. These findings provide important theoretical implications for deepening our understanding of the evolution characteristics of carbon sinks in China's dryland ecosystems and their response mechanisms to external environmental factors.

Keywords: gross primary productivity; climate change; response mechanism; geographic detector; China's drylands

1 Introduction

The terrestrial ecosystem carbon cycle involves two processes: carbon fixation and carbon emission. As a crucial component of the global ecosystem, terrestrial ecosystems play a significant role in the global carbon cycle. Photosynthesis serves as the primary source of carbon fixation in terrestrial ecosystems, regulating carbon dioxide and maintaining climate stability. Gross Primary Productivity (GPP), defined as the amount of organic carbon fixed by plants through photosynthesis per unit time, is an important parameter reflecting vegetation dynamics in ecosystems. Currently, research on GPP responses to climate change in China's drylands has primarily focused on temperature and precipitation. However, studies on soil water content and VPD—two climate factors that directly regulate vegetation drought stress—are relatively insufficient. Meanwhile, the key factors controlling GPP in China's drylands under the combined effects of multiple factors remain unclear. Clarifying the spatiotemporal evolution characteristics of GPP and its key influencing factors is crucial for understanding the carbon cycle and sustainable development of dryland ecosystems in China. Previous studies have shown that vegetation dynamics in China's arid and semi-arid regions are mainly controlled by precipitation and evapotranspiration, with soil water content and VPD serving as two primary drivers of vegetation drought stress. Therefore, this study, based on multi-source data and taking China's drylands as the research area, employed trend analysis, variability analysis, multi-factor partial correlation analysis, and geographic detector methods to investigate GPP characteristics at annual, interannual, and spatial scales, aiming to comprehensively understand the dynamic changes in vegetation carbon sequestration capacity and its response mechanisms to external environmental factors.

2 Study Area and Methods

2.1 Study Area Overview

China's drylands cover a vast area, mainly including the northeast, northwest, and southwest regions, involving multiple provinces (Figure 1). The region features large areas of grassland, desert, and cropland, with climate types primarily consisting of temperate continental and temperate monsoon climates. The diverse landform types exhibit elevation differences exceeding 8,000 m. The aridity status shows a gradually decreasing trend from southeast to northwest, with drought intensity increasing from coastal to inland areas.

2.2 Data Sources and Preprocessing

GPP Data: The MOD17A3H dataset was obtained from https://lpdaac.usgs.gov with a spatial resolution of 500 m and temporal resolution of 1 year. This dataset has been widely applied in terrestrial ecosystem productivity research and significantly improved pixel drift issues compared to previous versions.

Meteorological Data: Obtained from the China Meteorological Data Network (https://data.cma.cn/), including data from 824 meteorological stations. Variables included temperature (maximum, minimum, and average), precipitation, sunshine duration, average relative humidity, and wind speed. Daily potential evapotranspiration was calculated using the Penman formula, and VPD was computed as the difference between saturated and actual vapor pressure. The

ANUSPLIN software was used for spatial interpolation to generate monthly and annual raster meteorological datasets.

Soil Water Content: Derived from the European Centre for Medium-Range Weather Forecasts (ECMWF) fifth-generation product (https://www.ecmwf.int/) with 0.25° spatial resolution. Since soil water within 100 cm depth is the primary water source for plant growth in drylands, this study used the average soil water content data from 0–100 cm depth.

Digital Elevation Model (DEM): Obtained from the National Geospatial Data Cloud (https://www.gscloud.cn/) using SRTMDEMUTM 90M data to extract slope and aspect information.

Land Use Data: Downloaded from Zenodo (https://zenodo.org/). Vegetation type, soil type, landform type, GDP, and population data were obtained from the Resource and Environmental Science and Data Center of the Chinese Academy of Sciences (https://www.resdc.cn/). All data were unified to the same spatial projection and resolution.

2.3 Analysis Methods

Aridity Index Calculation: The AI was used to define dryland extent: AI = P/ET_0, where P is annual precipitation and ET_0 is annual potential evapotranspiration. Regions with $AI < 0.65$ were designated as drylands.

Trend Analysis and Significance Testing: The Theil-Sen median trend analysis and Mann-Kendall test were employed to analyze GPP spatiotemporal changes. This method effectively reduces the influence of outliers and measurement errors. The slope was represented by Slope, and trend significance was assessed at the 95% confidence level based on the Z-value from Mann-Kendall testing. Results were categorized into four patterns: significant increase (Slope > 0, $|Z| > 1.96$), non-significant increase (Slope > 0, $|Z| < 1.96$), significant decrease (Slope < 0, $|Z| > 1.96$), and non-significant decrease (Slope < 0, $|Z| < 1.96$).

Variability Analysis: The coefficient of variation (C) was used to characterize interannual fluctuation magnitude:

$$C_v = \frac{s}{\mu} \times 100\%$$

where s is the standard deviation,   is the multi-year mean, and n is the sample size. Higher C values indicate greater fluctuation and weaker resistance to interference.

Partial Correlation Analysis and Relative Contribution Calculation: At annual and monthly scales, four-factor partial correlation analysis was used to examine the relationship between GPP and each climate factor while controlling for the other three factors (precipitation, temperature, soil water content, VPD). The relative contribution rate of each climate factor to GPP variation was calculated based on partial correlation coefficients.

Geographic Detector: This method quantifies the driving forces behind spatial differentiation. Factor detection measured the explanatory power (q-value) of individual factors, while interaction detection assessed the combined effects of two factors. Interaction types included non-linear weakening, single-factor non-linear weakening, independence, dual-factor enhancement, and non-linear enhancement.

3 Results

3.1 Spatiotemporal Variation of GPP in China's Drylands

GPP showed an increasing trend from 2001 to 2020 at a rate of 4.96 g $\mathrm{C \cdot m^{-2} \cdot a^{-1}}$, with the minimum value (256.65 g $\mathrm{C \cdot m^{-2}}$) occurring in 2001 and the maximum (386.49 g $\mathrm{C \cdot m^{-2}}$) in 2020. Spatially, GPP gradually decreased from east to west, with higher values in the North China Plain, central-southern Loess Plateau (Shanxi and Shaanxi), and central Inner Mongolia. The western and Qinghai-Tibet Plateau regions showed lower values.

Approximately 95.38% of the dryland area exhibited increasing trends, with 64.72% showing significant increases, primarily distributed in North China, Northeast China, and the central Loess Plateau. Decreasing areas accounted for only 4.62%, scattered along the southeastern edge of the Qinghai-Tibet Plateau and the Ili River Valley in Xinjiang.

Different vegetation types showed varying GPP values and growth rates. Forests and wetlands had the highest GPP, while desert vegetation and alpine vegetation in the Qinghai-Tibet Plateau had the lowest. All vegetation types showed increasing trends, with cropland, broadleaf forest, mixed forest, and wetland growing faster than the regional average. Cropland showed the fastest growth rate, while alpine vegetation grew the slowest.

The coefficient of variation differed among vegetation types: desert vegetation and cropland showed high variability, while forests and wetlands exhibited low variability. Across drought gradients, extreme arid and arid regions showed higher variability than semi-arid and sub-humid dry regions.

3.2 Impact of Climate Change on GPP in China's Drylands

Spatial patterns of partial correlations between GPP and climate factors revealed that precipitation showed predominantly positive correlations, strongest in eastern North China, Northeast China, and Gansu-Ningxia regions. Temperature also showed mainly positive correlations, though generally weaker than precipitation, with stronger positive correlations in Gansu, Qinghai, Tibet, and northern Xinjiang. Negative correlations were mainly found along desert margins in Xinjiang.

Soil water content showed strong positive correlations in eastern grassland areas. VPD correlations were weaker overall. The relative contribution rates of climate factors to GPP interannual variation were: precipitation (31.65%), soil water content (23.66%), VPD (22.99%), and temperature (21.70%). Precipitation was the dominant factor across all drought gradients, while temperature's importance decreased with increasing aridity, indicating enhanced drought stress.

Among vegetation types, precipitation was the most important climate factor for all types except mixed forests and alpine vegetation, where temperature became more influential.

3.3 Spatial Driving Forces of GPP in China's Drylands

Factor detection results showed that soil type, landform type, AI index, land use type, elevation, precipitation, relative humidity, and soil water content significantly influenced GPP spatial patterns. Among climate factors, precipitation, relative humidity, and VPD showed strong explanatory power. Land use type was the most influential human activity factor, with its explanatory power increasing over time.

Interaction detection revealed that the explanatory power of interactions between any two factors exceeded that of single factors, showing dual-factor enhancement or non-linear enhancement. Interactions involving soil type demonstrated the strongest explanatory power, particularly with landform type, precipitation, AI index, land use type, relative humidity, and soil water content. Over time, interactions involving moisture-related factors (relative humidity, soil water content) with other factors strengthened.

4 Discussion

4.1 Spatiotemporal Characteristics of GPP in China's Drylands

GPP showed a decreasing trend from east to west, consistent with the moisture gradient. Forest and wetland areas had the highest GPP, while inland desert and alpine vegetation regions with harsh natural conditions had the lowest. The significant increase in GPP across 64.72% of the region reflects substantial improvement in carbon sequestration capacity. The fastest growth rates occurred in cropland, broadleaf forest, mixed forest, and wetland areas, widely distributed across the central Loess Plateau, Xinjiang, and Tibet—key regions for the Grain for Green Program. Previous studies have confirmed the significant carbon sink enhancement in the Loess Plateau since the 21st century, demonstrating that human measures effectively promoted GPP growth in China's drylands.

4.2 Response of GPP to Climate Change

From 2001 to 2020, China's drylands showed a "warming and wetting" trend, with temperature and precipitation increasing at rates of $0.08\ ^{\circ}\mathrm{C} \cdot (10\mathrm{a})^{-1}$ and $28.2\ \mathrm{mm} \cdot (10\mathrm{a})^{-1}$, respectively. Under these conditions, the relative influence of climate factors on GPP was: precipitation > soil water content > VPD > temperature. Different drought levels showed varying responses: as humidity increased, temperature's influence gradually increased while water stress effects decreased. However, moisture remained the primary control on GPP compared to thermal conditions.

Soil water, as the directly utilizable water source for plant growth in drylands, affects root development and indirectly influences vegetation GPP. Precipitation is the most important source for replenishing soil moisture, and increases in both precipitation and soil water jointly promote vegetation GPP increases, playing a dominant role in regulating GPP changes in China's drylands. VPD affects vegetation by regulating leaf stomatal conductance. The relative influence of VPD was greater in extreme arid and arid regions than in semi-arid and sub-humid dry regions, indicating that improved moisture conditions reduced VPD's negative impacts to some extent.

4.3 Factors Influencing GPP Spatial Patterns

Geographic detector analysis revealed that soil type and landform type were the key factors shaping GPP spatial patterns. Soil type determines comprehensive soil conditions and, together with soil texture and water content, exerts multifaceted influences on vegetation growth, explaining its higher explanatory power than soil water content alone. Landform type directly affects regional hydrothermal conditions, especially in China's drylands where forests are mainly distributed in mountain vertical belts while low-altitude areas have sparse vegetation, making carbon sequestration capacity more sensitive to topographic factors.

Moisture conditions (precipitation, AI index, relative humidity) were also important for shaping GPP spatial patterns. Land use type represented the most significant human activity factor. The explanatory power of land use type and its interaction with precipitation increased over time, reflecting the intensifying influence of ecological restoration projects.

5 Conclusions

This study investigated the spatiotemporal evolution characteristics and influencing factors of vegetation carbon sequestration capacity in China's drylands based on multi-source data. The main conclusions are:

1) Vegetation GPP in China's drylands showed a significant increasing trend from 2001 to 2020, with the significantly increasing area exceeding 64.72%, indicating substantially enhanced carbon sequestration capacity.

2) Precipitation and soil water content were the dominant climate factors driving GPP enhancement, with contribution rates of 31.65% and 23.66%, respectively. Temperature had the lowest contribution rate (21.70%). As

drought intensity increased, drought stress gradually strengthened, manifested by enhanced regulatory effects of precipitation and soil water content on GPP.

3) Soil type and landform type were the dominant factors influencing GPP spatial differentiation. Moisture conditions and land use type also played significant roles in shaping GPP spatial patterns. The explanatory power of interactions between any two factors exceeded that of single factors, with interactions involving soil type showing the strongest effects.

These findings provide important theoretical insights for understanding carbon sink evolution and response mechanisms to environmental factors in China's dryland ecosystems.

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