Time-lag and Cumulative Effects of Drought on Gross Primary Productivity in the Grasslands of Northern China (Postprint)

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Abstract

In recent years, with global warming, the increasing frequency of drought events has exerted a more significant impact on vegetation photosynthesis, while also severely affecting the balance of terrestrial ecosystems. Based on the Standardized Precipitation Evapotranspiration Index (SPEI base v.2.7) and Gross Primary Productivity dataset (GOSIF GPP), this study investigated the cumulative and lag effects of drought on GPP in the grasslands of northern China. Sen' s slope, Mann-Kendall (MK) trend test, and Mann-Kendall change point test were employed to examine the spatiotemporal variations of GPP and SPEI during the study period, while Pearson correlation analysis was used to explore the cumulative and lag effects of drought on GPP in northern grasslands. The results indicate that: (1) During 2001-2020, the multi-year average GPP in northern grasslands exhibited a spatial distribution pattern of high values in the Northeast region and low values in the Southwest region, while the multi-year average SPEI showed a pattern of low values in the Northeast region and high values in the Southwest region, and both annual average SPEI and GPP displayed an upward trend over time. (2) Drought had cumulative effects on 84.99% of the northern grassland area, with the longest cumulative time scales mainly concentrated at 3–4 months, covering 39.82% of northern grasslands; drought had lag effects on 63.11% of the northern grassland area, primarily occurring at 7 months, covering 19.73% of northern grasslands. (3) By comparing the variation trends of the two under different moisture conditions, it was found that the cumulative effect of drought on grassland GPP was stronger than the lag effect.

Full Text

Preamble

Title: Time Lag and Cumulative Effect of Drought on Gross Primary Productivity in the Grasslands of Northern China

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Abstract: In recent years, with global warming, the increasing frequency of drought events has exerted more significant impacts on vegetation photosynthesis and severely affected the balance of terrestrial ecosystems. Based on the Standardized Precipitation Evapotranspiration Index (SPEI base v2.7) and the GOSIF GPP dataset, this study investigates the cumulative and time-lag effects of drought on gross primary productivity (GPP) in the grasslands of northern China. Using Sen' s slope estimator, Mann-Kendall (MK) trend test, and Mann-Kendall mutation test, we analyzed the spatiotemporal variations of GPP and SPEI during the study period. Pearson correlation analysis was employed to explore the cumulative and lag effects of drought on GPP in northern grasslands. The results show that: (1) From 2001 to 2020, the multi-year average GPP exhibited a spatial distribution pattern of high values in the northeast and low values in the southwest, while the multi-year average SPEI showed the opposite pattern (low in the northeast and high in the southwest). Both GPP and SPEI annual averages showed an increasing trend over time. (2) Drought had a cumulative effect on 84.99% of the northern grassland area, with the longest cumulative time scale mainly concentrated at 3-4 months, covering 39.82% of the northern grassland. Drought had a lag effect on 63.11% of the northern grassland area, mainly occurring at a 7-month lag, covering 19.73% of the northern grassland. (3) By comparing variation trends under different water conditions, we found that the cumulative effect of drought on grassland GPP was stronger than the lag effect.

Keywords: grasslands of northern China; drought; gross primary productivity; time-lag effect; cumulative effect

Introduction

Over the past few decades, global grassland climate has undergone significant changes, a phenomenon that will continue into the future. Climate factors including temperature, precipitation, and solar radiation have notable impacts on grassland growth and pastoral development. Since the 1980s, changes in atmospheric circulation systems from the troposphere to the stratosphere have intensified the aridification trend in northern China, with frequent drought events and large-scale persistent droughts. Meanwhile, drought intensity and duration in northwestern China will continue to strengthen and increase in the future.

Vegetation responses to climate are often complex. When drought occurs, it affects ecosystems through lag, cumulative, and legacy effects that influence vegetation growth conditions. The cumulative effect of drought refers to the impact of water deficit over a period (spanning months or even years) on vegetation growth, where persistent water stress in soil can be used to assess vegetation drought tolerance. The legacy effect refers to the influence of previous drought conditions on current vegetation growth, such as reduced vegetation productivity caused by drought in the previous year. The lag effect means that drought affects not only current vegetation but also has a temporal delay in its impact. For example, vegetation growth may be more significantly affected by conditions from the previous month or even several months than by current month conditions. Kolus et al. found that drought affects mortality factors in forest trees, thereby disrupting forest ecosystem stability, and that vegetation responses to drought have a certain time lag. Studies on the lag effects of drought on vegetation dynamics in alpine watersheds of the Tibetan Plateau have found differences in lag effects between upper and middle reaches, with a one-month lag in the upper reaches. Many studies have discovered that drought has lag and cumulative effects on the Normalized Difference Vegetation Index (NDVI). Research on autumn phenology has shown strong cumulative and lag effects of drought. Studies based on SPEI have found that the cumulative effect of drought on vegetation growth is greater than the lag effect. Systematic investigations of drought frequency, duration, and severity on GPP have shown that drought impacts have both direct and lagged effects.

Drought affects vegetation growth and development, leading to decreased ecosystem productivity and interfering with carbon-water exchange between the atmosphere and ecosystems. Gross Primary Productivity (GPP), defined as the amount of organic carbon fixed by plants through photosynthesis per unit time, is an important indicator for assessing carbon sinks and ecological regulation processes and promoting ecosystem carbon cycling. GPP directly reflects actual photosynthesis and is more sensitive to drought conditions, making it frequently used to characterize drought impacts on vegetation. Grasslands in northern China are highly responsive to precipitation, with rich vegetation types serving as an important ecological protection barrier for China and even South Asia. Due to their special geographic environment, these ecosystems are fragile with poor resistance to disturbance and are significantly affected by drought. Therefore, this study aims to investigate the relationships between different grassland types and drought in northern China, exploring the lag and cumulative effects of drought on different grassland types to understand the underlying mechanisms and provide effective strategies for mitigating drought impacts on grassland primary productivity.

1. Materials and Methods

1.1 Study Area

The study area is located in the grasslands of northern China (73°33 ~126°04 E, 26°50 ~53°23 N), covering approximately 3.13$×10^{6}$ km^2, which accounts for 79.7% of the national grassland area. The annual mean temperature ranges from -3.1 to 8.9°C, and annual precipitation ranges from 31.46 to 898.04 mm. The study area includes six provinces or autonomous regions: Inner Mongolia Autonomous Region, Gansu Province, Ningxia Hui Autonomous Region, Xinjiang Uygur Autonomous Region, Qinghai Province, and Tibet Autonomous Region. Northern China contains numerous grassland types, including alpine meadow, temperate meadow, alpine steppe, desert steppe, typical steppe, and meadow steppe. Affected by climate change and human activities, this region belongs to arid and semi-arid areas with fragile ecological environments.

1.2 GOSIF GPP Data

The GOSIF GPP dataset is derived from OCO-2 satellite data, providing a spatial resolution of 0.05° and temporal coverage from 2001 to 2020. This study utilized GPP data for the northern grassland region of China from 2001 to 2020 (http://globalecology.unh.edu).

1.3 Vegetation Type Data

Vegetation type data were obtained from the Resource and Environment Science and Data Center of the Chinese Academy of Sciences (https://www.resdc.cn). Using ArcGIS 10.2, the 1:1,000,000 vegetation type dataset was reclassified. After extracting the study area by mask, grassland types in northern China were divided into six categories: meadow steppe, typical steppe, desert steppe, alpine steppe, temperate meadow, and alpine meadow.

1.4 SPEI Dataset

The Standardized Precipitation Evapotranspiration Index (SPEI) quantifies drought severity and duration. This study used SPEI base v2.7 to characterize drought conditions in northern China' s grasslands, obtained from DIGITAL.CSIC (https://digital.csic.es/handle/10261/268088). This dataset provides global coverage of standardized precipitation evapotranspiration index data at 0.5° spatial resolution, including time scales from 1 to 48 months. The dataset was preprocessed and interpolated to match the spatial resolution of GOSIF GPP data.

2. Methods

2.1 Trend Analysis and Mann-Kendall (MK) Test

The Theil-Sen Median method, also known as Sen' s slope estimator, is a robust non-parametric statistical trend calculation method. This approach is computationally efficient, insensitive to measurement errors and outliers, and commonly used for analyzing long time series data. The trend β is calculated as the median of all pairwise slopes between data points. A positive β indicates an increasing trend, while a negative β indicates a decreasing trend.

The Mann-Kendall (MK) test is a non-parametric statistical test that does not require normally distributed samples and is not affected by missing values or outliers. It is frequently used for significance testing of long time series trends. The test statistic S is calculated based on the signs of differences between all pairs of observations. The variance of S and standardized test statistic Z are then computed. When $|Z| > Z\alpha$ (where $\alpha = 0.05$), the trend is considered statistically significant.

2.2 Mann-Kendall Mutation Test

The Mann-Kendall method can also detect abrupt changes in meteorological data. For a time series $x_1, \cdots, x$, a rank sequence is constructed where each element represents the cumulative count of observations exceeding previous values. Under the assumption of random independence, the mean and variance of the rank sequence can be calculated. The standardized statistic sequence UF is computed from the rank sequence. Given a significance level α, if $|UF\ | > U\alpha$, the sequence shows a significant trend change. When $UF > 0$, it indicates a continuous growth trend. The intersection point of UF and UB curves within the confidence interval [-1.96, 1.96] indicates the year of mutation.

2.3 Time-Lag Effect Analysis

To analyze the time-lag effect of drought on northern grassland GPP, Pearson correlation analysis was used to calculate correlation coefficients between GPP and SPEI at different lag times (0-12 months). The analysis begins with one-month SPEI, then progressively increases the lag interval. When the correlation coefficient r reaches its maximum value, i is considered the longest correlation month. For example, if the correlation between GPP and SPEI from 7 months prior is highest, the lag time scale is 7 months. This reveals how drought conditions from previous months affect current grassland GPP.

2.4 Cumulative Effect Analysis

To explain the cumulative impact of drought on northern grassland GPP, Pearson correlation analysis was used to calculate correlation coefficients r between GPP and SPEI at different cumulative time scales (1-12 months). The month length with the maximum coefficient is considered the longest cumulative time scale for drought impact on grassland vegetation. For instance, if the 4-month SPEI shows the highest correlation, then 4 months is the longest cumulative time. This reveals how persistent drought conditions affect GPP.

To assess the potential influence of hydrological conditions on cumulative and lag effects, this study selected SPEI-3 as the annual water balance condition, which can reveal annual wet-dry gradients. Annual average SPEI values were divided into intervals along the water balance gradient, and regression analysis was performed to reveal relationships between average lag/cumulative time and water balance conditions.

3. Results

3.1 Spatial Distribution and Temporal Variation Characteristics of GPP in Northern Grasslands

Temporal Distribution Characteristics: Figure 2 shows that from 2001 to 2020, annual GPP in northern grasslands fluctuated between 188.20-265.50 g $C \cdot m^{-2} \cdot a^{-1}$, with an average growth rate of 2.7101 g $C \cdot m^{-2} \cdot a^{-1}$ and an overall upward trend. Mann-Kendall mutation analysis revealed that the UF curve remained mostly above 0 during the study period, indicating an upward trend, with 2008 as a decreasing point. The UF and UB curves intersected near 2015, with the intersection point within the confidence interval, indicating a significant mutation in 2015, after which the upward trend became significant.

To further investigate seasonal variation trends, GPP changes were analyzed by season using MK tests. Spring GPP showed a mutation in 2015, but it was not significant. After 2015, the UF curve exceeded the 0.05 significance level, indicating a significant downward trend. Summer GPP showed no significant trend. Autumn GPP had multiple intersection points between UF and UB curves, indicating unstable changes, but none were significant. Winter GPP showed an upward trend between 2001-2011, followed by a significant downward trend.

Spatial Distribution Characteristics: Figure 5 shows that the multi-year average GPP in northern grasslands from 2001-2020 ranged from 0-2228.83 g $C \cdot m^{-2} \cdot a^{-1}$, with an average of 421.38 g $C \cdot m^{-2} \cdot a^{-1}$, showing an overall pattern of high values in the northeast and low values in the southwest. High-value areas appeared in most parts of Tibet and Qinghai, dominated by alpine meadow and alpine steppe. Low-value areas were concentrated in most parts of Inner Mongolia, Xinjiang central region, and Qinghai-Gansu border region, dominated by desert steppe, typical steppe, and temperate meadow.

Variation Trends: Sen' s slope estimator was applied pixel-by-pixel to analyze GPP trends from 2001-2020, with significance testing. Results showed annual trend values fluctuated between -38.37 and 74.08 g $C \cdot m^{-2} \cdot a^{-1}$. Areas showing increasing trends accounted for 63.10% of the study area, distributed mainly in most parts of Inner Mongolia, southern Tibet, northern Xinjiang, central-southern Qinghai, most of Ningxia, and central Gansu. Areas with essentially no change accounted for 29.28%, while decreasing areas accounted for only 7.62%.

3.2 Spatial Distribution and Temporal Variation Characteristics of SPEI in Northern Grasslands

Temporal Distribution Characteristics: Figure 8 shows that from 2001-2020, annual SPEI in northern grasslands fluctuated between -1.41 and 0.87, with an average of -0.11, indicating normal conditions. The overall pattern showed low values in the northeast and high values in the southwest, with high-value areas in most parts of Tibet and Qinghai (dominated by alpine meadow and alpine steppe) and low-value areas in most parts of Inner Mongolia (dominated by desert steppe, typical steppe, and temperate meadow). The UF and UB curves intersected in 2015 and 2018, but neither passed significance tests, indicating no significant change.

Seasonal analysis revealed that spring, summer, and autumn SPEI patterns were consistent with the annual pattern (northeast low, southwest high), while winter showed the opposite pattern (southwest low, northeast high). Spring SPEI decreased at a rate of -0.285 per decade, showing aridification. Summer SPEI increased at 0.218 per decade, with 2001 and 2015 being the driest and wettest years, respectively. Autumn SPEI increased at 0.004 per decade, with no mutation after 2011. Winter SPEI decreased at 0.014 per decade, with 2002 and 2010 being the wettest and driest years.

Variation Trends: Pixel-by-pixel trend analysis showed annual SPEI trend values ranged from -0.12 to 0.15. Increasing trends accounted for 58.05% of the study area, particularly in northeastern Inner Mongolia and southern Qinghai. Decreasing trends accounted for 41.95%, mainly in northern Xinjiang, most of Tibet, southwestern Qinghai, and southwestern Inner Mongolia.

3.3 Cumulative Effects of Drought on GPP in Northern Grasslands

Analysis of cumulative effects using Pearson correlation between GPP and SPEI at different time scales showed that 84.99% of northern grassland area exhibited positive correlations, indicating cumulative effects. Only northern Xinjiang, western Tibet, and parts of northeastern Inner Mongolia showed negative correlations. The average correlation coefficient was 0.08, with high correlation areas (r_{cum} > 0.4) found in northeastern Xinjiang (correlation of 0.48).

The longest cumulative time scale was concentrated at 3-4 months, covering 39.82% of northern grassland area. The peak area percentage occurred at 4 months (20.27%), mainly distributed in northeastern Tibet, southeastern Qinghai, and central Inner Mongolia. The 3-month scale accounted for 19.55%, while 11-12 month scales accounted for only 2.22%, mainly in western Tibet and northeastern Qinghai.

The relationship between water balance conditions and cumulative effects showed that annual average SPEI was significantly positively correlated with average cumulative correlation coefficient ($R^2 = 0.879$). As drought conditions alleviated (SPEI increased), the average positive cumulative coefficient first decreased then increased, indicating that cumulative effects were strongest in semi-arid or semi-humid regions and weaker in relatively dry or wet regions. Average cumulative time was negatively correlated with annual average SPEI, suggesting that better water supply (higher SPEI) resulted in shorter vegetation response times to drought.

3.4 Time-Lag Effects of Drought on GPP in Northern Grasslands

Analysis of time-lag effects showed that 63.11% of northern grassland area exhibited lag effects, with only parts of Qinghai showing negative correlations. The average correlation coefficient was 0.07, with high correlation areas found in northeastern Xinjiang (correlation of 0.45).

The longest lag time scale was concentrated at 7 months, covering 41.59% of northern grassland area, distributed across Tibet, Qinghai, Xinjiang, and central and northeastern Inner Mongolia. The 6-month lag showed the strongest response (19.73%), mainly in central-southern Tibet, southwestern Qinghai, northern Xinjiang, and northeastern Inner Mongolia. The 5-month scale accounted for 13.81%, while 10-11 month scales showed the smallest proportion (4.14%).

The relationship between water balance and lag effects showed that annual average SPEI was significantly negatively correlated with average lag correlation coefficient ($R^2 = 0.78$). As water balance conditions improved, average lag time decreased from 7.5 to 6.5 months, indicating that worsening drought trends resulted in longer vegetation response times.

3.5 Time-Lag and Cumulative Effects on Different Grassland Types

Further investigation of different grassland types revealed significant differences in correlation levels between GPP and drought. Most grassland types showed cumulative effects stronger than lag effects, except for meadow steppe and temperate meadow. Meadow steppe showed the strongest lag effect (0.14) and longest lag time (7.5 months), while desert steppe showed the strongest cumulative effect (0.13). All grassland types had longer cumulative times than lag times, with meadow steppe having the longest cumulative time (8.5 months).

4. Discussion

After drought responses conclude, they continue to affect ecosystem carbon sequestration and create memory effects that confuse vegetation responses, leading to multiple response states over time (lag and cumulative effects). Pearson correlation analysis of GPP and SPEI relationships in northern grasslands showed that drought lag effects occurred in most areas, with the longest lag time of 7 months accounting for 19.73%, indicating that soil moisture conditions during the growing season affect vegetation growth with certain time lags.

Similar to lag effects, 84.99% of northern grassland showed cumulative effects, meaning drought can inhibit grassland productivity. High correlation areas (correlation of 0.48) were found in northeastern Xinjiang, dominated by desert steppe—the most drought-resistant grassland ecosystem with annual precipitation \$ \$200 mm, making it more vulnerable to drought impacts. The longest cumulative time scale was concentrated at 3-4 months, which aligns with findings about drought severity and duration impacts on vegetation. GPP can effectively capture short-term variations in soil moisture status.

Comparing cumulative and lag effects across grassland types revealed that cumulative effects were generally stronger than lag effects. However, different grasslands showed varying response times: meadow steppe had the longest cumulative and lag times (8.5 and 7.5 months, respectively), while desert steppe showed the strongest cumulative effect. The relationship between water conditions and cumulative effects was positive, while the relationship with lag effects was negative, indicating that vegetation in arid regions is more susceptible to drought stress. The cumulative effect of drought on GPP was stronger than the lag effect in northern grasslands.

The unique geographic location and hydrothermal conditions of northern China' s grasslands make ecosystems vulnerable, especially the Tibetan Plateau where vegetation is extremely sensitive to climate change. Meadow steppe is most susceptible to drought impacts, requiring particular attention to soil moisture conservation and restoration. The study' s findings on SPEI-GPP correlations align with previous research, though differences in vegetation types and their evolved physiological strategies may explain variations in drought responses. Future work should focus on maintaining soil moisture in northern grasslands and addressing both cumulative and lag effects, particularly the stronger cumulative effects, by implementing proactive measures to protect grassland vegetation.

5. Conclusion

This study investigated the lag and cumulative effects of drought on GPP in northern China' s grasslands from 2001-2020 using GPP and SPEI-3 data. The main conclusions are:

1. The multi-year average GPP showed a spatial pattern of high values in the northeast and low values in the southwest, while SPEI showed the opposite pattern. The study area experienced alternating dry and wet periods, with both GPP and SPEI annual averages showing increasing trends over time. Among grassland types, GPP ranked as: meadow steppe > temperate meadow > typical steppe > alpine meadow > desert steppe > alpine steppe.
2. Drought had lag effects on 63.89% of northern grassland area, mainly at 7-

month lag (19.7% coverage). As drought conditions intensified, the degree of lag effects increased.

3. Drought had cumulative effects on 84.98% of northern grassland area, with the longest cumulative time scale concentrated at 3-4 months (39.81% coverage). Cumulative effects were stronger in arid regions than in semi-arid or humid regions.
4. Different grassland types showed varying responses. The lag effect ranking was: meadow steppe > desert steppe > temperate meadow > typical steppe > alpine steppe > alpine meadow. The cumulative effect ranking was: meadow steppe > temperate meadow > typical steppe > alpine meadow > desert steppe > alpine steppe.

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