Postprint: Impacts of Multi-temporal Scale Drought on Vegetation Dynamics in Shaanxi Province

Authors: Ning Zekai, Song Cheng, Zhang Yajun, Li Qi, Li Pei

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Abstract

Analyzing the spatiotemporal responses of vegetation to drought across different time scales and quantifying the relative impact of drought on vegetation change are of great significance for implementing ecosystem restoration and disaster prevention and mitigation in a manner adapted to local conditions. Based on observational data from 85 meteorological stations in Shaanxi Province during 2000–2020, this study calculates the Standardized Precipitation Evapotranspiration Index (SPEI), combines it with the Normalized Difference Vegetation Index (NDVI), and employs trend analysis, partial correlation analysis, and ridge regression analysis to investigate the spatiotemporal variation characteristics of SPEI and NDVI and their correlations, and to quantify the relative influence of seasonal SPEI on annual-scale NDVI variation. The results show that: (1) During 2000–2020, the drought frequency in spring in Shaanxi Province was the highest, reaching 42.6%, followed by summer (29.7%), while autumn and winter were 21.6% and 21.9%, respectively. Northern Shaanxi had the highest drought frequency (29.6%), followed by southern Shaanxi (28.7%) and the Guanzhong region (27.9%). Approximately 89.7% of the province exhibited a slow wetting trend, among which the area proportion showing a wetting trend was spring > summer > autumn > winter. (2) The mean NDVI values in southern Shaanxi, the Guanzhong region, and northern Shaanxi were 0.89, 0.77, and 0.57, respectively, and vegetation showed significant improvement in about 88.0% of the province. (3) In approximately 53.2% of Shaanxi Province, SPEI and NDVI showed a non-significant positive correlation, while 6.9% of the area exhibited a significant correlation, mainly distributed in northern Shaanxi; regions with a non-significant negative correlation were mainly located in the Guanzhong region. (4) Areas where the relative influence of spring, summer, autumn, and winter SPEI on annual-scale NDVI variation exceeded 50% accounted for about 31.1%, 23.7%, 0.5%, and 15.3% of the provincial area, respectively.

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Full Text

Effects of Drought on Vegetation Dynamics at Multiple Time Scales in Shaanxi Province

NING Zekai[1,2], **SONG Cheng**[1,2], **ZHANG Yajun**[3], **LI Qi**[4], **LI Pei**[1,2]

[1]Key Laboratory of Subsurface Hydrology and Ecological Effects in Arid Region of the Ministry of Education, School of Water and Environment, Chang' an University, Xi' an 710054, Shaanxi, China

[2]Key Laboratory of Ecological Hydrology and Water Security in Arid Region of the Ministry of Water Resources, Chang' an University, Xi' an 710054, Shaanxi, China

[3]College of Land and Resources, Hebei Agricultural University, Baoding 071001, Hebei, China

[4]Power China Northwest Engineering Corporation Limited, Xi' an 710065, Shaanxi, China

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Abstract

Analyzing the spatiotemporal response of vegetation to drought at different time scales and quantifying the relative impact of drought on vegetation dynamics are essential for implementing targeted ecological restoration and disaster mitigation measures. Based on meteorological observations from 85 stations in Shaanxi Province from 2000 to 2020, this study calculated the Standardized Precipitation Evapotranspiration Index (SPEI) and combined it with the Normalized Difference Vegetation Index (NDVI). Using trend analysis, partial correlation analysis, and ridge regression, we investigated the spatiotemporal variation characteristics of SPEI and NDVI, examined their correlations, and quantified the relative contributions of seasonal drought to annual vegetation changes. The results show that: (1) From 2000 to 2020, spring drought frequency was highest in Shaanxi Province at 42.6%, followed by summer (29.7%), autumn (21.6%), and winter (21.9%). Northern Shaanxi exhibited the highest drought frequency (29.6%), followed by southern Shaanxi (28.7%) and central Shaanxi (27.9%). Approximately 89.7% of the province showed a slow wetting trend, with 21.6% of the area showing significant wetting. (2) The average NDVI values for southern, central, and northern Shaanxi were 0.89, 0.77, and 0.57, respectively. About 88.0% of the province experienced significant vegetation improvement, with the most pronounced improvement in northern Shaanxi. (3) Approximately 53.2% of the province showed a non-significant positive correlation between SPEI and NDVI, while only 6.9% showed a significant positive correlation, mainly in northern Shaanxi. Non-significant negative correlations were primarily distributed in central Shaanxi. (4) The areas where the relative impact of seasonal SPEI on annual NDVI changes exceeded 50% accounted for 31.1% (spring), 23.7% (summer), 0.5% (autumn), and 15.3% (winter) of the province, respectively.

Keywords: Standardized Precipitation Evapotranspiration Index; Normalized Difference Vegetation Index; correlation analysis; relative impact coefficient

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1 Introduction

Drought disasters have become increasingly normalized with global warming and represent one of the most severe natural disasters worldwide. Vegetation, as a critical component of ecosystems, suffers from water deficiency during frequent drought events, which disrupts normal physiological activities, inhibits growth, and can even cause mortality. In northwestern and northern China, severe drought has become a major natural disaster constraining socioeconomic development and affecting ecological environments. Therefore, studying drought impacts on vegetation is of great significance for agriculture, ecology, and the economy.

Common drought indices include the Palmer Drought Severity Index (PDSI), Standardized Precipitation Index (SPI), and Standardized Precipitation Evapotranspiration Index (SPEI). The PDSI considers temperature effects but uses a fixed time scale. The SPI is suitable for multi-scale drought calculations but ignores temperature effects. The SPEI combines the advantages of both, can sensitively identify precipitation and temperature variations, and is widely applied. For instance, Tao et al. used the SPEI index to reveal spatiotemporal patterns of winter drought in Inner Mongolia through frequency statistics, trend analysis, and hotspot analysis. Wang et al. analyzed drought characteristics in Southwest China from 1961-2013 based on SPEI, examining drought intensity, frequency, and trends.

Vegetation exhibits seasonal and periodic patterns, with varying coverage and photosynthesis/respiration intensity across seasons, leading to different drought responses. The Normalized Difference Vegetation Index (NDVI) is widely used due to its sensitivity, high spatiotemporal resolution, and ability to eliminate radiation variation effects. Many studies have investigated vegetation responses to drought using NDVI, such as Wu et al. who examined vegetation trends and drivers in the Yellow River Basin, and Li et al. who studied multi-scale drought effects on vegetation. However, current research mainly focuses on differences among vegetation types and lag/cumulative effects, without quantifying the relative impacts of different time-scale droughts on vegetation.

Shaanxi Province, located in northwestern China, spans multiple climate zones with uneven precipitation distribution, resulting in significant regional differences in drought disasters and vegetation coverage. This study analyzes the relationship between seasonal and annual-scale drought and vegetation cover, examines correlations between SPEI and NDVI, and quantifies the relative impacts of seasonal drought on annual vegetation changes.

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2 Data and Methods

2.1 Study Area

Shaanxi Province (31°42′~39°35′N, 105°29′~111°15′E) is located in western inland China, comprising northern Shaanxi (Shaanbei), central Shaanxi (Guanzhong), and southern Shaanxi (Shannan) from north to south. The terrain is high in the north and south and low in the middle. The province spans multiple climate zones, including mid-temperate monsoon, warm-temperate monsoon, and north subtropical monsoon climates, leading to uneven spatiotemporal precipitation distribution. The diverse topography and climate conditions create varied ecosystem types and significant regional differences in vegetation coverage, making it an important transitional zone for climate and biodiversity in China [Figure 1: see original paper].

2.2 Data Sources

2.2.1 Standardized Precipitation Evapotranspiration Index (SPEI) Daily meteorological data from 2000-2020 were collected from 85 meteorological stations in Shaanxi Province (including precipitation, average wind speed, average temperature, sunshine hours, and relative humidity) from the National Meteorological Data Platform (http://data.cma.cn/). Missing and anomalous values were filled using multi-year daily averages. The Penman-Monteith formula was used to calculate daily potential evapotranspiration (ET_0), followed by water deficit (precipitation minus ET_0) and SPEI values at various time scales (SPEI-3 for seasonal, SPEI-12 for annual). Detailed calculation methods are described in reference [**?**]. Drought categories based on SPEI values are: no drought (SPEI > -0.5), mild drought (-1 < SPEI ≤ -0.5), moderate drought (-1.5 < SPEI ≤ -1), severe drought (-2 < SPEI ≤ -1.5), and extreme drought (SPEI ≤ -2).

2.2.2 Normalized Difference Vegetation Index (NDVI) NDVI time series data (250 m × 250 m resolution) from 2000-2020 were obtained from NASA LAADS Web (https://lpdaac.usgs.gov). Maximum Value Composites (MVC) were used to generate seasonal and annual NDVI values. To match meteorological data, NDVI data were resampled to 1 km × 1 km resolution.

2.3 Methods

2.3.1 Trend Analysis The Theil-Sen Median slope estimator is a non-parametric method for calculating trends in time series data, widely used in meteorology, vegetation, and hydrology. Compared with traditional linear regression, it is insensitive to outliers and provides more accurate linear trend estimates [**?**]. The slope is calculated as:

$$\text{Slope} = \text{median}\left(\frac{X_j - X_i}{j - i}\right), \quad 1 < i < j < n$$

where X_i and X_j are observations at time points i and j. Trend direction is determined by: Slope < -0.005 (decreasing), -0.005 $\leq$ Slope $\leq$ 0.005 (stable), and Slope > 0.005 (increasing).

The Mann-Kendall trend test is a non-parametric method for assessing significant trends. The test statistic Z indicates significance level; $|Z| > 1.96$ indicates significance at the 95% confidence level. Slope and Z values were used to classify trend significance (Table 1).

2.3.2 Partial Correlation Analysis Partial correlation analysis examines the relationship between two variables while controlling for other variables. The partial correlation coefficient is calculated as:

$$r_{xy\cdot z} = \frac{r_{xy} - r_{xz}r_{yz}}{\sqrt{(1-r_{xz}^2)(1-r_{yz}^2)}}$$

where r_{xy}, r_{xz}, and r_{yz} are simple correlation coefficients. Positive $r_{xy\cdot z}$ indicates positive correlation, negative indicates negative correlation, with absolute values closer to 1 indicating stronger correlations. Significance was tested using t-tests.

2.3.3 Ridge Regression Analysis Ridge regression quantifies the contribution of multiple independent variables to dependent variable changes [**?**]. This study used it to quantify seasonal SPEI contributions to annual NDVI changes (expressed as relative impact coefficients). Data were normalized to eliminate unit and dimension effects:

$$x_{im} = \frac{x_i - \min(x)}{\max(x) - \min(x)}$$

where x_{im} is normalized data, $\min(x)$ and $\max(x)$ are minimum and maximum values. Annual NDVI was regressed against seasonal SPEI values:

$$Y_m = \sum_{i=1}^{4} a_i x_{im} + b$$

where Y_m is normalized annual NDVI, a_i is the regression coefficient for season i, and b is the intercept. Relative impact coefficients for each season were calculated as:

$$\text{nrc}_i = \frac{|a_i|}{\sum_{i=1}^{4}|a_i|} \times 100\%$$

where nrc_i is the relative impact coefficient for season i.

3 Results

3.1 Multi-Scale Drought Characteristics

3.1.1 Spatial Distribution of Drought Frequency Based on data from 2000-2020, drought frequency across seasons and the year ranged from 23.8%–61.9% (spring), 14.3%–52.4% (summer), 4.7%–38.1% (autumn), 0%–57.1% (winter), and 9.5%–47.6% (annual). Multi-station average frequencies were 42.6% (spring), 29.7% (summer), 21.6% (autumn), and 27.9% (winter). Northern Shaanxi had the highest average drought frequency (29.6%), followed by southern Shaanxi (28.7%) and central Shaanxi (27.9%). The frequency of moderate or worse drought was also highest in northern Shaanxi (15.1%), with some stations reaching 57.1% total drought frequency and 42.9% moderate+ drought frequency [Figure 2: see original paper].

3.1.2 Drought Trends Annual drought trends showed significant spatial variation. Approximately 89.7% of the province exhibited a slow wetting trend, with 21.6% showing significant wetting, mainly in southern and western central Shaanxi. Small areas in eastern central Shaanxi showed slow drying trends [Figure 3e: see original paper].

Seasonally, spring showed wetting trends in 68.8% of the province (22.2% significantly), mainly in southern and western central Shaanxi, while northern Shaanxi showed drying trends (6.9% significantly) [Figure 3a: see original paper]. Summer drying trends concentrated in eastern southern and central Shaanxi (28.3% of province), with wetting trends elsewhere, especially in central-southern northern Shaanxi (12.5% significantly wetting) [Figure 3b: see original paper]. Autumn showed minimal significant trends, with 40.7% slowly wetting and 57.4% slowly drying [Figure 3c: see original paper]. Winter drying trends covered 87.6% of the province, with 16.5% significantly drying in central Guanzhong, northern Shaanbei, and southwestern Shannan [Figure 3d: see original paper].

3.2 Multi-Scale Vegetation Cover Characteristics

From 2000-2020, NDVI showed clear spatiotemporal differences. Average seasonal NDVI values were 0.60 (spring), 0.81 (summer), 0.71 (autumn), and 0.44 (winter), reflecting seasonal water-heat conditions. Regional averages were 0.89 (southern Shaanxi), 0.77 (central Shaanxi), and 0.57 (northern Shaanxi), showing climate zone and topographic controls on vegetation distribution.

Overall, 88.0% of the province showed significant vegetation improvement, with northern Shaanxi improving most prominently. Degraded areas (2.3% significantly degraded, 9.7% slightly degraded) concentrated in central Shaanxi and around Hanzhong City, associated with urbanization. Seasonally, spring had the highest degradation proportion (13.9% of province, 5.2% significant), while summer showed the most improvement (91.3% of province, 82.6% significant) [Figure 4: see original paper].

3.3 Correlations Between Multi-Scale SPEI and NDVI

At the annual scale, SPEI-NDVI correlations showed clear regional patterns: positive correlations dominated northern Shaanxi, while negative correlations dominated central Shaanxi. Non-significant positive correlations covered 53.2% of the province, mainly in northern Shaanxi. Significant positive correlations occurred in 6.9% of the province, also concentrated in northern Shaanxi. Non-significant negative correlations covered 37.6% of the province, distributed in central and southern Shaanxi [Figure 5e: see original paper].

Seasonal correlations showed distinct characteristics. Spring: 74.3% of the province showed positive correlations (63.0% significant, mainly in northern Shaanxi) [Figure 5a: see original paper]. Summer: 71.7% positive correlations (15.8% significant, in northern and eastern southern Shaanxi) [Figure 5b: see original paper]. Autumn: 68.1% positive correlations (13.3% significant, in northern Shaanxi and eastern southern Shaanxi) [Figure 5c: see original paper]. Winter: 62.3% positive correlations (the smallest proportion), with 25.7% significant and 37.7% non-significant positive correlations, mainly in southern Shaanxi and western central Shaanxi [Figure 5d: see original paper]. Negative correlations were smallest in winter (37.7%) and largest in summer (28.3%).

3.4 Relative Impact of Seasonal Drought on Annual NDVI Changes

Ridge regression quantified the relative impact coefficients of seasonal SPEI on annual NDVI changes. Spring drought had the greatest relative impact on annual vegetation changes, followed by summer and winter, with autumn having the smallest impact. Using 50% relative impact as a threshold, spring impacts exceeded 50% in 31.1% of the province, mainly in southern Shaanxi and western central Shaanxi. Summer impacts exceeded 50% in 23.7% of the province, concentrated in northern Shaanxi. Winter impacts exceeded 50% in 15.3% of the province, mainly in central Shaanxi and near Hanzhong City. Autumn impacts exceeded 50% in only 0.5% of the province, showing the smallest relative impact [Figure 6: see original paper].

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4 Discussion

4.1 Multi-Scale Drought and Vegetation Characteristics in Shaanxi Province

Shaanxi’ s unique topography and climate cause frequent droughts with significant regional differences. Spring is the most severe drought season, with northern Shaanxi most prone to drought, especially in spring and winter, consistent with previous research [?, ?]. Drought in Shaanxi is driven by atmospheric circulation, continental monsoon climate, geography, and human activities. Atmospheric circulation and monsoons affect precipitation distribution and drought intensity [?]. The north-south high, middle-low terrain blocks moisture transport to central Shaanxi, while severe soil erosion in northern Shaanxi reduces water retention capacity [?, ?]. Intensive human activities (mining, groundwater extraction, deforestation) also exacerbate drought risks [?].

Overall drought trends have improved, but autumn and winter show drying trends, with 87.6% of the province experiencing intensified winter drought. Climate transitions from humid to semi-humid, semi-arid, and arid from south to north. Wang et al. [?] found that meteorological drought impacts on vegetation vary by climate zone. Northern Shaanxi shows positive SPEI-NDVI correlations, especially in spring, because shallow-rooted grasses and shrubs are sensitive to moisture changes. Central Shaanxi shows negative correlations, likely because irrigation during drought reduces drought impacts on cropland-dominated vegetation [?]. Southern Shaanxi correlations are generally non-significant, possibly because forest vegetation is less responsive to climate variations than grasslands [?].

4.2 Vegetation Response to Drought in Shaanxi Province

This study used seasonal time scales because vegetation phenology shows seasonal differences. Results show that overall vegetation-drought responses are non-significant, consistent with Li et al. [?], suggesting that ecological projects (e.g., Grain-for-Green) have enhanced vegetation resilience. However, responses vary spatially: spring impacts concentrate in high-coverage southern Shaanxi where rapid spring growth increases water demand; summer impacts concentrate in northern Shaanxi where high temperatures make drought a primary growth-limiting factor; winter impacts concentrate in central Shaanxi and near Hanzhong where human activities (irrigation, management) reduce drought sensitivity.

Vegetation improvement is significant in northern and southern Shaanxi, linked to ecological restoration projects (afforestation, enclosure). Degraded areas concentrate in urbanizing central Shaanxi and around Hanzhong City, consistent with existing research [?, ?].

4.3 Limitations and Outlook

This study reveals seasonal vegetation-drought responses in Shaanxi. However, vegetation type differences (grassland in northern Shaanxi, cropland in central Shaanxi, forest in southern Shaanxi) affect drought response mechanisms, which were not considered. Future research should explore vegetation type-specific responses. Additionally, human activities have become another important driver of vegetation dynamics [?]. Vegetation growth is also influenced by non-climatic factors (geomorphology, groundwater, soil properties) [?]. This study focused on vegetation-drought relationships; future work could integrate multi-source data (land use/cover, soil, topography, socioeconomic factors) to build a more comprehensive driving framework and quantitatively analyze relative contributions of various factors to reveal vegetation dynamic mechanisms more systematically.

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5 Conclusions

Based on 2000-2020 SPEI and NDVI data, this study analyzed spatiotemporal variations and correlations between drought and vegetation at multiple scales, and quantified seasonal drought impacts on annual vegetation changes. The main conclusions are:

1) Drought frequency and trends in Shaanxi Province show significant seasonal and regional differences. The average drought frequency was 28.6%, highest in spring (42.6%), followed by summer (29.7%), winter (21.9%), and autumn (21.6%). Northern Shaanxi had the highest drought frequency (29.6%), followed by southern Shaanxi (28.7%) and central Shaanxi (27.9%). Approximately 89.7% of the province showed a slow wetting trend, with 21.6% significantly wetting. Wetting trends were most pronounced in spring and summer, while drying trends dominated autumn and winter, especially severe in winter.

2) Average NDVI values were highest in southern Shaanxi (0.89), followed by central Shaanxi (0.77) and northern Shaanxi (0.57). About 88.0% of the province showed significant vegetation improvement, most prominent in northern Shaanxi. Seasonally, the proportion of area with significant improvement was 82.3% (spring), 91.3% (summer), 87.7% (autumn), and 82.6% (winter).

3) At the annual scale, 53.2% of the province showed non-significant positive SPEI-NDVI correlation, 6.9% showed significant positive correlation (mainly in northern Shaanxi), and 37.6% showed non-significant negative correlation (mainly in central and southern Shaanxi). Seasonally, positive correlation area proportions were 74.3% (spring), 71.7% (summer), 68.1% (autumn), and 62.3% (winter).

4) Spring drought had the greatest relative impact on annual NDVI changes, followed by summer and winter, with autumn having the smallest impact. Areas where relative impact exceeded 50% accounted for 31.1% (spring), 23.7% (summer), 0.5% (autumn), and 15.3% (winter) of the province. Spring impacts concentrated in southern Shaanxi and western central Shaanxi; summer impacts in northern Shaanxi; winter impacts in central Shaanxi and near Hanzhong City; autumn impacts were minimal.

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