

Postprint: Sensitive Response of Vegetation Phenology to Seasonal Drought on the Loess Plateau

Authors: Ji Zhenxia, Hou Qingqing

Date: 2022-04-16T00:39:10+00:00

Abstract

In the context of global warming, the increased frequency and intensity of drought events have led to significant changes in vegetation diversity in terrestrial ecosystems. Studying the response of vegetation phenology to seasonal drought is of great importance for the conservation of ecosystems on the Loess Plateau. Based on MODIS remote sensing Normalized Difference Vegetation Index (MODIS NDVI: MOD13Q1) data and monthly gridded precipitation and temperature data, ridge regression analysis was employed to investigate the sensitivity response of vegetation phenology to seasonal drought on the Loess Plateau. The results indicate that: (1) The previous summer drought index (Standardized Precipitation Evapotranspiration Index, SPEI) and previous autumn SPEI delay the Start of Season (SOS), while early winter SPEI and current spring SPEI advance vegetation SOS. Early winter SPEI is more likely to delay the End of Season (EOS) compared to current spring SPEI and current autumn SPEI, whereas current summer SPEI advances vegetation EOS. (2) Vegetation phenology on the Loess Plateau exhibits significant spatial heterogeneity in response to seasonal SPEI. When drought intensity weakens in early winter within Qinghai Province, it advances vegetation SOS; intensified drought in current summer causes most vegetation on the Loess Plateau to end growth earlier. (3) Different vegetation types on the Loess Plateau show distinct phenological responses to seasonal SPEI. Shrub SOS is more susceptible to drought than forest SOS and grassland SOS, while grassland SOS is most vulnerable to early winter drought. This study can provide a scientific basis for vegetation on the Loess Plateau to cope with seasonal drought.

Full Text

Sensitive Response of Vegetation Phenology to Seasonal Drought in the Loess Plateau

JI Zhenxia¹, HOU Qingqing², PEI Tingting^{1, 3}, CHEN Ying^{1, 3}, XIE Baopeng³, WU Huawu^{4, 5}

¹College of Resources and Environment, Gansu Agricultural University, Lanzhou 730070, Gansu, China

²College of Pratacultural Science, Gansu Agricultural University, Lanzhou 730070, Gansu, China

³College of Management, Gansu Agricultural University, Lanzhou 730070, Gansu, China

⁴Key Laboratory of Grassland Ecosystem (Gansu Agricultural University), Ministry of Education, Lanzhou 730070, Gansu, China

⁵Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing 210008, Jiangsu, China

Abstract: Under the background of global warming, the increasing frequency and intensity of drought events are causing significant changes in vegetation diversity within terrestrial ecosystems. Vegetation phenology profoundly influences vegetation productivity, carbon storage, and carbon cycling in terrestrial ecosystems. However, due to the inherent complexity and uncertainty of drought, as well as differences in resistance and resilience among vegetation types, few studies have examined the effects of seasonal drought on different vegetation phenologies.

Based on MODIS NDVI data, land use/cover data, and monthly gridded precipitation and temperature data, this study calculated the start of season (SOS), end of season (EOS), and standardized precipitation evapotranspiration index (SPEI) for vegetation on the Loess Plateau from 2001 to 2018. Using ridge regression analysis, we investigated the sensitivity response of vegetation phenology to seasonal drought. The results show that: (1) Drought intensification in the previous summer and autumn delayed vegetation SOS, whereas weakened drought in the winter at the beginning of the year and spring of the current year advanced SOS. Winter SPEI was more likely to delay EOS compared to spring and autumn SPEI of the same year, while summer drought intensification caused vegetation to end growth earlier. (2) Both SOS and EOS exhibited obvious spatial heterogeneity in their response to seasonal SPEI. When winter drought weakened at the beginning of the year in Qinghai Province, vegetation SOS advanced. Summer drought intensification led to premature ending of growth for most vegetation on the Loess Plateau. The response of most vegetation to drought during the growth cessation period was weaker than in other seasons. (3) Seasonal SPEI delayed shrub SOS but advanced grassland SOS, with shrubs being more susceptible to drought than forests and grassland. Winter drought at the beginning of the year had the greatest impact on grassland SOS compared to other seasons. Meanwhile, forests, shrubs, and grassland all ended

growth earlier as summer drought intensified. This study reveals the response patterns of vegetation phenology to seasonal drought on the Loess Plateau and provides a scientific basis for vegetation responses to water stress and ecological environmental protection.

Keywords: vegetation phenology; seasonal drought; sensitivity response; Loess Plateau

1.1 Study Area Overview

The Loess Plateau is located in northwestern China, spanning $100^{\circ}52' \sim 114^{\circ}33' \text{ E}$ and $33^{\circ}41' \sim 41^{\circ}16' \text{ N}$, with elevations ranging from 83 to 5010 m. The climate is constrained by both latitude/longitude and topography, transitioning from a humid monsoon climate in the southeast to an inland arid climate in the northwest. The annual mean temperature ranges from 3.6 to 14.3°C , and annual precipitation increases from northwest to southeast, varying between 300 and 800 mm. Annual total solar radiation reaches 5.0×10^6 to $6.3 \times 10^6 \text{ kJ} \cdot \text{m}^{-2}$, while potential evapotranspiration far exceeds precipitation, ranging from 865 to 1274 mm. Summer experiences the highest frequency of moderate, severe, and extreme drought events, though annual-scale drought across the Loess Plateau is predominantly mild, mainly distributed across most areas of Shaanxi and Shanxi provinces. Influenced by climate, vegetation distribution exhibits a southeast-northwest horizontal zonation.

1.2 Data Sources and Processing

This study used the Normalized Difference Vegetation Index (NDVI) to extract vegetation phenology parameters. NDVI data were obtained from NASA's MODIS land cover dynamics product (MOD13Q1) at 250 m spatial resolution. Following previous studies, $\text{NDVI}_{\text{mean}} = 0.05$ was used as the threshold to exclude non-vegetation pixels. The time series was reconstructed using maximum value compositing to remove noise, with a window size set for rational function fitting. The dynamic threshold method proposed by Jönsson and Eklundh was applied, with dynamic thresholds set at 20.0% and 80.0% based on validation against field phenology data from Shapotou, Haibei, and Ordos stations, as well as published literature. Specifically, the time point when the rising NDVI curve reached 20.0% of the distance between minimum and maximum values was defined as SOS, while the time point when the descending curve reached 80.0% of this distance was defined as EOS. It should be noted that the Timesat 3.2 software extracts phenology from n years of data to produce $n-1$ years of phenological parameters. Therefore, the final dataset comprised phenology data for 2001-2018, which has been validated in previous literature and demonstrated to be reliable.

Monthly gridded precipitation and temperature data were obtained from the China Meteorological Data Service Center (<http://data.cma.cn>) at 0.5° hori-

zontal resolution. The Standardized Precipitation Evapotranspiration Index (SPEI) was calculated from these data to assess drought severity and duration, offering advantages over other drought indices. After computing seasonal SPEI for each grid point in R, the data were interpolated to 250 m resolution raster datasets using ANUSPLIN software. The 1-12 month scale SPEI reflects seasonal drought characteristics: winter (December-February), spring (March-May), summer (June-August), and autumn (September-November). Since vegetation SOS occurs in spring, we used SPEI from the previous summer, previous autumn, early winter, and current spring in our calculations. EOS occurs in autumn, so we used SPEI from early winter, current spring, current summer, and current autumn.

Land use/cover data were derived from the MCD12Q1 product at 500 m resolution. Considering the environmental management achievements since the implementation of the Grain for Green Project, we extracted only areas where land use/cover types remained unchanged during 2001-2018, merging them into forest, shrub, grassland, cropland, and other categories. This study focused on forest, shrub, and grassland.

1.3 Research Methods

Ridge regression analysis was employed to explore phenology sensitivity to seasonal SPEI. The multivariate linear regression model is expressed as:

$$Y = X\beta + \varepsilon$$

where Y is the n -dimensional observation vector of the dependent variable; X is the $n \times p$ observation matrix of independent variables; β is the p -dimensional parameter vector; and ε is the n -dimensional random error vector. The ordinary least squares estimator is $\hat{\beta} = (X^T X)^{-1} X^T Y$. While theoretically sound, least squares estimation can yield unstable parameter estimates and unreasonable results due to multicollinearity. Therefore, this study used ridge regression to eliminate multicollinearity effects. The ridge regression estimator is:

$$\hat{\beta}_{RR} = (X^T X + kI)^{-1} X^T Y$$

where $\hat{\beta}_{RR}$ represents the sensitivity coefficient of independent variables to the dependent variable; k is the ridge parameter; and I is the identity matrix. In this study, phenology was the dependent variable and seasonal SPEI the independent variable. All variables were linearly detrended in R, and the resulting regression coefficients represent sensitivity coefficients of each independent variable.

2.1 Spatiotemporal Characteristics of Vegetation Phenology on the Loess Plateau

The spatial distribution of vegetation SOS on the Loess Plateau is shown in Figure 2. SOS primarily occurs between days 90–150, gradually delaying from southeast to northwest. The interannual trend shows that SOS advanced significantly during 2001–2018 at an average rate of 0.38 days per year. The earliest SOS occurred in the southern parts of Ningxia and Qinghai (around day 114), while the latest occurred in the northern Shaanxi–Shanxi region (around day 132).

The spatial distribution of vegetation EOS is shown in Figure 2. EOS primarily occurs between days 260–310. Overall, vegetation in the Ningxia Plateau and Qinghai region ended growth earlier, while southern areas ended later. The interannual trend indicates that EOS was delayed significantly during 2001–2018 at an average rate of 2.83 days per year.

The interannual variation slopes (Figure 3) show that the delayed trend of EOS was more pronounced than the advanced trend of SOS, with the EOS slope greater than the SOS slope, indicating a clear advancement trend for SOS.

2.2 Sensitivity of Vegetation Phenology to Seasonal SPEI on the Loess Plateau

The sensitivity of vegetation phenology to different seasonal SPEI values is shown in Figure 4. For SOS, positive sensitivity pixels (where drought delays phenology) accounted for 61.0% for previous summer SPEI and 61.2% for previous autumn SPEI, indicating that most vegetation experienced delayed growth. In contrast, negative sensitivity pixels dominated for early winter and spring SPEI, reflecting advanced growth when drought weakened. Winter SPEI showed the largest proportion of significantly positive sensitivity pixels (70.1%, $P < 0.05$), particularly in Qinghai, where weakened winter drought advanced vegetation budding, likely because appropriate temperatures promoted vegetation development.

For EOS, positive and negative sensitivity differences were evident. The proportion of pixels with significant positive sensitivity to winter SPEI was 73.4% ($P < 0.05$), indicating that weakened winter drought delayed vegetation EOS. The sensitivity coefficients for summer and autumn SPEI were smaller, suggesting weaker responses during growth cessation. Negative sensitivity was observed in parts of Gansu, Ningxia, and Shaanxi, while positive sensitivity appeared in southeastern areas, indicating that excessive summer drought caused premature growth ending.

2.3 Spatial Patterns of Phenology Sensitivity to Seasonal SPEI

The spatial distribution of sensitivity coefficients reveals pronounced spatial heterogeneity (Figure 5). Significant positive sensitivity of SOS to winter SPEI was

widespread across the study area ($P < 0.05$), with high coefficients concentrated in the northeastern Loess Plateau. In contrast, sensitivity to previous summer and autumn SPEI was relatively small. For EOS, significant negative sensitivity to summer SPEI was scattered throughout the region, while positive sensitivity appeared in southeastern areas.

2.4 Sensitivity of Different Vegetation Types to Seasonal SPEI

Comparative analysis of different vegetation phenology responses (Figure 6) shows varying sensitivity degrees: shrub > forest > grassland. Shrub SOS was delayed by seasonal SPEI, while grassland SOS was advanced. Both winter and spring SPEI delayed shrub SOS, with winter SPEI having a greater effect, indicating shrubs are more drought-sensitive than forests and grassland. All vegetation types showed negative sensitivity coefficients for summer SPEI, meaning drought intensification caused earlier EOS. The impact of autumn SPEI on EOS was greatest for shrubs, followed by grassland and forest.

3 Discussion

Drought significantly impacts vegetation activity in arid and semi-arid regions. This study found that winter and spring SPEI sensitivity coefficients were substantial. Since smaller SPEI values indicate more severe drought, weakened winter and spring drought advanced vegetation SOS. This likely occurs because spring warming combined with reduced drought stress promotes vegetation budding after the cold, dry winter. Summer drought intensification caused earlier EOS, possibly because hot, stormy summer weather increases potential evapotranspiration in the Loess Plateau, where precipitation is scarce. Accumulated drought stress reduces soil water availability for carbon synthesis, weakening photosynthesis, closing stomata, and causing premature leaf senescence.

The spatial heterogeneity of phenology responses to seasonal drought suggests drought increases regional phenological variability. Previous studies identified temperature and precipitation as primary drivers of vegetation growth and phenology. This analysis demonstrates that drought severity is also a crucial factor. The cumulative and lag effects of drought on vegetation occur within 0–3 months and 1–3 months, respectively, confirming that both pre-phenology and concurrent drought affect phenology. Different vegetation types exhibit varying physiological characteristics and functional strategies, leading to different sensitivities. Shrub water use efficiency is more climate-sensitive than that of forests and grassland, corroborating our finding that shrubs are most vulnerable to seasonal drought.

4 Conclusions

- (1) Drought intensification in the previous summer and autumn delayed vegetation SOS, whereas weakened drought in winter and spring advanced SOS. Winter SPEI was more likely to delay EOS than spring and autumn

SPEI. Summer drought intensification caused vegetation to end growth earlier.

- (2) Vegetation SOS and EOS showed obvious spatial heterogeneity in response to seasonal SPEI. In Qinghai, weakened winter drought advanced SOS. Summer drought intensification led to premature ending of growth for most vegetation on the Loess Plateau. The response of most vegetation to drought during the growth cessation period was weaker than in other seasons.
- (3) Seasonal SPEI delayed shrub SOS but advanced grassland SOS, with shrubs being more susceptible to drought than forests and grassland. Winter drought had the greatest impact on grassland SOS compared to other seasons. Forests, shrubs, and grassland all ended growth earlier as summer drought intensified.

This study reveals the response patterns of vegetation phenology to seasonal drought on the Loess Plateau and provides a scientific basis for vegetation responses to water stress and ecological environmental protection.

References

- [1] IPCC. Climate change 2013: The physical science basis: The summary for policymakers of the working group I contribution to the fifth assessment report[R]. Cambridge, UK: Cambridge University Press, 2013.
- [2] Zhang X Y, Ge Q S, Zheng J Y. Relationships between climate change and vegetation in Beijing using remote sensed data and phenological data[J]. Chinese Journal of Plant Ecology, 2004, 28(4): 499-506.
- [3] Vicente Serrano S M, Gouveia C, Camarero J J, et al. Response of vegetation to drought timescales across global land biomes[J]. Proceedings of the National Academy of Sciences, 2012, 110(1): 52-57.
- [4] Peng J, Wu C Y, Zhang X Y, et al. Satellite detection of cumulative and lagged effects of drought on autumn leaf senescence over the northern Hemisphere[J]. Global Change Biology, 2019, 25(6): 2014-2027.
- [5] Hanson P J, Weltzin J F. Drought disturbance from climate change: Response of United States forests[J]. Science of the Total Environment, 2000, 262(3): 205-220.
- [6] Anderegg W R, Berry J A, Field C B. Field linking definitions, mechanisms, and modeling of drought induced tree death[J]. Trends in Plant Science, 2012, 17(12): 693-700.
- [7] Wen Y Y, Liu X P, Xin Q C, et al. Cumulative effects of climatic factors on terrestrial vegetation growth[J]. Journal of Geophysical Research: Biogeosciences, 2019, 124(4): 789-806.

- [8] Ma X, Huete A, Moran S, et al. Abrupt shifts in phenology and vegetation productivity under climate extremes[J]. *Journal of Geophysical Research: Biogeosciences*, 2015, 120: 2036-2052.
- [9] He Z, Du J, Chen L, et al. Impacts of recent climate extremes on spring phenology in arid mountain ecosystems in China[J]. *Agricultural and Forest Meteorology*, 2018, 260-261: 31-40.
- [10] Mou C X, Sun G, Luo P, et al. Flowering responses of alpine meadow plant in the Qinghai Tibetan Plateau to extreme drought imposed in different periods[J]. *Chinese Journal of Applied and Environmental Biology*, 2013, 19(2): 272-279.
- [11] Yuan M, Zhao L, Lin A, et al. Impacts of preseason drought on vegetation spring phenology across the northeast China Transect[J]. *Science of the Total Environment*, 2020, 738: 140297, doi: 10.1016/j.scitotenv.2020.140297.
- [12] Xie B N, Qin Z F, Wang Y, et al. Monitoring vegetation phenology and their response to climate change on Chinese Loess Plateau based on remote sensing[J]. *Transactions of the Chinese Society of Agricultural Engineering*, 2015, 31(15): 153-160.
- [13] Ji Z X, Pei T T, Chen Y, et al. Vegetation phenology change and its response to seasonal climate changes on the Loess Plateau[J]. *Acta Ecologica Sinica*, 2021, 41(16): 1-13.
- [14] Liu J, Wen Z M, Gang C C. Normalized difference vegetation index of different vegetation cover types and its responses to climate change in the Loess Plateau[J]. *Acta Ecologica Sinica*, 2020, 40(2): 678-691.
- [15] Pei T T, Li X Y, Wu H W, et al. Sensitivity of vegetation water use efficiency to climate and vegetation index in Loess Plateau, China[J]. *Transactions of the Chinese Society of Agricultural Engineering*, 2019, 35(5): 119-125, 319.
- [16] Zhao A Z, Yu Q Y, Feng L L, et al. Evaluating the cumulative and lag effects of drought on grassland vegetation: A case study in the Chinese Loess Plateau[J]. *Journal of Environmental Management*, 2020, 261(5): 110214, doi: 10.1016/j.jenvman.2020.110214.
- [17] Zhang Q, Kong D D, Singh V P, et al. Response of vegetation to different time scales drought across China: Spatiotemporal patterns, causes and implications[J]. *Global & Planetary Change*, 2017, 152(5): 1-11.
- [18] Huang W J. Alpine grassland phenology response to climate change over Tibetan Plateau[D]. Lanzhou: Lanzhou University, 2019.
- [19] Lloyd D. A phenological classification of terrestrial vegetation cover using shortwave vegetation index imagery[J]. *International Journal of Remote Sensing*, 1990, 11(12): 2269-2279.
- [20] Jönsson P, Eklundh L. Seasonality extraction by function fitting to time-series of satellite sensor data[J]. *IEEE Transactions on Geoscience and Remote*

Sensing, 2002, 40(8): 1824-1832.

[21] Liu Z P, Wang Y Q, Shao M G, et al. Spatiotemporal analysis of multi-scalar drought characteristics across the Loess Plateau of China[J]. Journal of Hydrology, 2016, 534(534): 281-299.

[22] Zou L, Yu J Y, Xia J, et al. Temporal spatial variation characteristics of drought in the Weihe River Basin based on SPEI[J]. Arid Land Geography, 2020, 43(2): 329-338.

[23] Hou Q Q, Pei T T, Chen Y, et al. Variations of drought and its trend in the Loess Plateau from 1986 to 2019[J]. Chinese Journal of Applied Ecology, 2021, 32(2): 649-660.

[24] Shi Y F, Liang S Q, Peng S Z. Spatiotemporal variation of climate drought in Loess Plateau region during 1901–2017[J]. Bulletin of Soil and Water Conservation, 2020, 40(1): 283-289, 325.

[25] Zhang Y R, Zhang Y J, Jin Z H, et al. The temporal and spatial characteristics of summer drought in the Loess Plateau based on SPEI[J]. Ecology and Environmental Sciences, 2019, 28(7): 1322-1331.

[26] Qin G X, Wu J, Li C B, et al. Grassland vegetation phenology change and its response to climate changes in north China[J]. Chinese Journal of Applied Ecology, 2019, 30(12): 4099-4107.

[27] Ni L, Wu J, Li C B, et al. Temporal and spatial variations in natural grassland phenology in China over the last 30 years[J]. Acta Prataculturae Sinica, 2020, 29(1): 1-12.

[28] An B, Xiao W W, Zhang S L, et al. Spatial and temporal characteristics of surface temperature in the Loess Plateau during 1960–2017[J]. Arid Land Geography, 2021, 44(3): 778-785.

[29] Zhao J T, Wang Y J, Su B D, et al. Spatiotemporal distributions of temperature, precipitation, evapotranspiration, and drought in the Indus River Basin[J]. Arid Land Geography, 2020, 43(2): 349-359.

[30] Yao J Q, Dilinuer Tuoliewubieke, Chen J, et al. Identification of drought events and correlations with large scale ocean atmospheric patterns of variability: A case study in Xinjiang, China[J]. Atmosphere, 2019, 10(2): 94, doi: 10.3390/atmos10020094.

[31] Yang Y T, Guan H D, Batelaan O, et al. Contrasting responses of water use efficiency to drought across global terrestrial ecosystems[J]. Scientific Reports, 2016, 17(6): 23284, doi: 10.1038/srep23284.

[32] Wang Y N, Lu Q H. The accurate expression of three knowledge points about multicollinearity[J]. Journal of Wenzhou University (Natural Science Edition), 2019, 40(3): 7-12.

- [33] Gan S J, Wang Q J. Estimation for a class of linear regression models[J]. Journal of Central China Normal University (Natural Sciences Edition), 2021, 55(3): 351-355.
- [34] Walker E, Birch J B. Influence measures in ridge regression[J]. Technometrics, 1988, 30(2): 221-227.
- [35] Huang W L, Zhang Q, Kong D D, et al. Response of vegetation phenology to drought in Inner Mongolia from 1982 to 2013[J]. Acta Ecologica Sinica, 2019, 39(13): 4953-4965.
- [36] Liu D, Wang T, Yang T, et al. Deciphering impacts of climate extremes on Tibetan grasslands in the last fifteen years[J]. Science Bulletin, 2019, 64(7): 446-454.
- [37] Wu J W, Miao C Y, Zheng H Y, et al. Meteorological and hydrological drought on the Loess Plateau, China: Evolutionary characteristics, impact, and propagation[J]. Journal of Geophysical Research: Atmospheres, 2018, 123(20): 569-584.
- [38] Chu H S, Venevsky S, Wu C, et al. NDVI-based vegetation dynamics and its response to climate changes at Amur Heilongjiang River Basin from 1982 to 2015[J]. Science of the Total Environment, 2019, 650(2): 2051-2062.
- [39] Ping Z, Wen A, Zhang X, et al. Soil conservation and sustainable environment in the Loess Plateau of China[J]. Environmental Earth Sciences, 2013, 68(3): 633-639.
- [40] Simmons.

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

Source: ChinaXiv –Machine translation. Verify with original.