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Responses of vegetation productivity to multi-scale drought in Loess Plateau, China

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ABSTRACT

Drought affects land surface dynamics. Quantifying the response of vegetation productivity to variations in drought events at different time-scales is crucial for evaluating the potential impacts of climate change on terrestrial ecosystems. Utilizing the Standardized Precipitation Evapotranspiration Index (SPEI) and Normalized Difference Vegetation Index (NDVI), this study evaluated the response of vegetation productivity to different time-scales of drought (SPEI-3, SPEI-6, SPEI-12, and SPEI-24, with 3, 6, 12 and 24 months of accumulation, respectively) in the growing season (April to October), as well as the spring, summer and autumn of the Loess Plateau (LP) by the maximum Pearson correlation (r_{max}). Results indicated that: (1) major areas (91.49%, 88.81%, 94.41% and 79.20%) of the LP were highly controlled by drought at the different time-scales during 1982–2013. However, high spatial and seasonal differences occurred during different time-scales, with the maximum influence in summer at 3-month time (SPEI-3); (2) r_{max} showed that 98.47%, 45.91%, 89.80% and 75.33% of the LP show significant correlation ($P < 0.05$) between the SPEI and vegetation productivity in the growing season, and the spring, summer and autumn; (3) vegetation productivity of arid regions responded mostly in the 3-month time (SPEI-3), and vegetation productivity of semi-arid and semi-humid regions mostly responded at the 12-month time (SPEI-12) or 24-month time (SPEI-24) in the growing season; and lastly, (4) the r_{max} was higher in the 3-month time for grassland and cultivated vegetation and in the 12-month time for the shrub land, need-leaf forest and broadleaf forest.

1. Introduction

Drought is a natural climate phenomenon which occurs when water availability is significantly below normal levels over a long period and the supply cannot satisfy the existing demand (Vicente-Serrano et al., 2013). Recently research has shown that with global warming, the frequency and duration of droughts have increased significantly, and the impact of drought on water resources, and especially natural ecosystems, is becoming increasingly acute (Dai, 2013; Zhang et al., 2017a, 2017b). Quantifying and predicting the response of terrestrial ecosystems to drought is a crucial challenge for climate research (Vicente-Serrano et al., 2013). Understanding the responses of vegetation productivity to drought can help to improve our knowledge of the vulnerability of ecological environment to climate change (Vicente-Serrano et al., 2013). Currently, a general theory of the effects of drought on terrestrial ecosystems is lacking due to both their inherent complexity and the limited knowledge of seasonal drought impacts on vegetation productivity over multiple temporal resolutions (Knapp and Smith, 2001; Vicente-Serrano et al., 2013).

One of the major difficulties in the understanding of drought is the selection of indicative variables. Single indicative variables can hardly assess drought conditions such as drought duration, intensity, magnitude, and space-time change (Vicente-Serrano et al., 2013). In recent years, several climatic drought indices (e.g. the Palmer Drought Severity Index (PDSI) (Palmer, 1965), the Standardized Precipitation Index (SPI) (McKee et al., 1993) and the Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al., 2010)) have been widely used to assess drought conditions. The PDSI is based on a soil water balance equation, but this index has numerous deficiencies, including the main criticism that the PDSI has a fixed temporal scale

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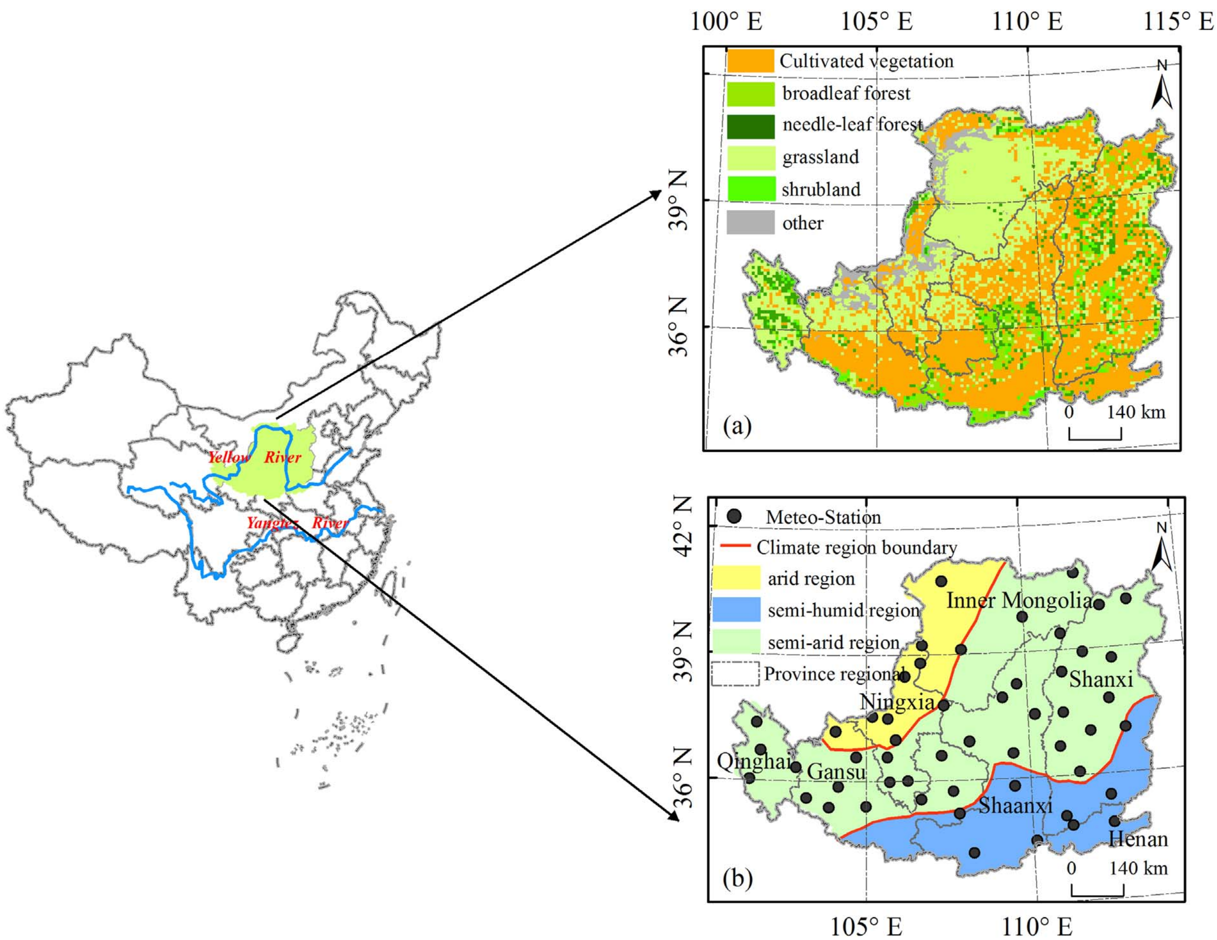

Fig. 1. Geographical maps of the Loess Plateau: (a) the distribution of vegetation types, (b) 52 weather stations meteorological stations and 3 climate regions.

(Vicente-Serrano et al., 2013). However, drought as a multi-scalar phenomenon has been widely accepted and used as a framework to monitor drought impacts on terrestrial ecosystems (McKee et al., 1993; Vicente-Serrano et al., 2013; De Keersmaecker et al., 2017). The SPI has been accepted by the World Meteorological Organization (WMO) as the reference drought index, due to the fact that it can be calculated at multiple temporal resolutions (Guttman, 1998). Many studies analyzed the response of vegetation activity to drought by using the SPI (Wang et al., 2015; Vicente-Serrano et al., 2006). However, the calculation of SPI only incorporates precipitation data, and other crucial factors (e.g. evapotranspiration and temperature) that can affect the frequency of drought are not included (Vicente-Serrano et al., 2010). Some studies have indicated that warming processes significantly increased evapotranspiration and increased drought stress on a regional scale (Rebetez et al., 2006; Adams et al., 2009). Because of this finding, it is important to evaluate the relationship between land surface dynamics and drought under global warming conditions (Breshears et al., 2005). SPEI was established by Vicente-Serrano et al. (2010). It is a multi-scalar drought index used to determine both water deficit and surplus at different timescales (Li et al., 2015). The SPEI is calculated from mean monthly temperature and precipitation data which has been collected from meteorological stations. This drought indicator considers the multi-scalar character of the SPI, varies in evaporation demand of the PDSI, and is better to characterize recent drought events that have occurred under climatic warming, especially in semi-arid and arid regions (Vicente-Serrano et al., 2013).

The Normalized Difference Vegetation Index (NDVI) is a good indicator for monitoring vegetation productivity and has been widely used to assess vegetation degradation, ecosystem features, and the physiologic drought conditions of vegetation and patterns of vegetation productivity (Zhang et al., 2013; Wang et al., 2003). The third-generation Global Inventory Modeling and Mapping Studies (GIMMS3g) with a 1/12° spatial resolution is considered an ideal dataset to analyze the relationships between climate variability and land surface dynamics for long time series and large-scale areas. Using the GIMMS3g dataset, Gouveia et al. (2017) analyzed drought impacts on NDVI in the entire Mediterranean basin. They found large areas of Mediterranean basin highly controlled by drought. Zhang et al. (2017a) evaluated the response of vegetation to multiple temporal resolution droughts across China, and showed that vegetation productivity and SPEI were significantly positively correlated in most regions of China.

The Loess Plateau is an important agricultural region and covers a large area in the northwest of China (Liu et al., 2016). Drought hazards frequently occur and affect the healthy and sustainable development of agricultural, socio-economic and ecological environment (Shi and Shao, 2000; Liu et al., 2016). Zhang et al. (2016) analyzed the responses of vegetation cover to drought in the Loess Plateau (LP). They found that vegetative growth was responsive to droughts (SPEI-12, 12 months of accumulation.). However, only SPEI-12 was taken into account in the study of vegetation response to drought. Responses of vegetation activity to seasonal droughts were not included in the study. With observed increases in global intensity and frequency of drought under climate change conditions, knowledge of the impact in terrestrial ecosystems is crucial, especially as it pertains to vegetation responses to drought events, so that future projections of climate change can be planned for. However, few studies have evaluated the impact of seasonal droughts on land surface dynamics, and there are still many uncertainties regarding the sensitivity of vegetation to seasonal droughts over different time-scales at regional scale processes in the LP.

In this context, the aim of the present study is to analyze the effects