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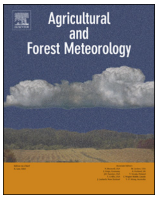

Diverse responses of vegetation growth to meteorological drought across climate zones and land biomes in northern China from 1981 to 2014

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ABSTRACT

Improving our understanding of present and future impacts of drought on the vegetation in northern China is heightened by expectations that drought would increase its vulnerability and subsequently accelerate land degradation. The response of vegetation activity to drought and the underlying mechanisms are not well known. By using the third-generation Normalized Difference Vegetation Index (NDVI) and the Standardized Precipitation Evapotranspiration Index (SPEI), we investigated the relationship between NDVI and SPEI, across different climate regimes and land cover types, and determined the dominant time-scales at which different biome types respond to drought during the period of 1981–2014. Our results showed that biome response is coupled with drought trends in most regions of northern China. The highest correlation between monthly NDVI and SPEI at different time scales (1–48 months) assessed the impact of drought on vegetation, and the time scales resulting in the highest correlation were an effective indicator of drought resistance, which was related to the interactive roles of mean water balance and divergent drought survival traits and strategies. Diverse responses of vegetation to drought were critically dependent on characteristic drought time-scales and different growing environments. This study highlighted the most susceptible ecosystem types to drought occurrence under current climate, including temperate steppes, temperate desert steppes, warm shrubs and dry forests. Given that drought will be more frequent and severe under future climate scenarios, it may threaten the survival of mesic ecosystems, such as temperate meadows, alpine grasslands, dwarf shrubs, and moist forests not normally considered at drought risk. We propose that future research should be focused on arid and semi-arid ecosystems, where the strongest impact of drought on vegetation is occurring and the need for an early warning drought system is increasingly urgent.

1. Introduction

More frequent and severe drought has been forecast in the 21st century, particularly in the mid-latitudes (Sheffield and Wood, 2008). Increases in drought are driven primarily by decreased precipitation with increased evapotranspiration from higher temperatures (Trenberth et al., 2014). Drought is recognized as the world's most costly and pressing natural hazard that influences water resource systems, agricultural production and natural ecosystems (Mishra and Singh, 2010). Water availability acts as the main driver of vegetation distribution and productivity in arid and semi-arid regions (Neilson, 1995; Churkina and Running, 1998). Evidence is accumulating that semi-arid ecosystems dominate the trend and inter-annual variability in the land CO_2 sink, and are highly sensitive to drought trends (Zhao and Running, 2010; Ahlström et al., 2015; Huang et al., 2016). Therefore, understanding the response of dryland ecosystems to drought is important for assessing vegetation vulnerability to climate extreme events (Smith et al., 2014) and has strong implications for enhancing drought mitigation and preparedness (Wilhite et al., 2007).

Northern China is located in the mid-latitude East Asia with arid, semi-arid and dry sub-humid regions accounting for approximately 34%, 27% and 16% of its total land area, respectively. The Taklimakan and Gobi Deserts constitute two major dust sources over East Asia (Tanaka and Chiba, 2006). The vegetation in northern China plays a pivotal role in the prevention and control of land degradation (Wang et al., 2015), which has a significant effect on the national ecological security (Miao et al., 2015). Soil water availability is a primary constraint on the survival of sand-binding vegetation (Li et al., 2013).

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Under global warming, severe and extreme droughts have been more frequent in the eastern and central portions of northern China since the late 1990s (Yu et al., 2014; Zhang et al., 2016), and a wetting trend in the western region has weakened since the 1980s (Ma and Fu, 2006). In addition, an increased incidence of intensified drought is expected by the middle of the 21st century (Wang and Chen, 2014; Leng et al., 2015). In this context, the need to evaluate the potential impact of drought on vegetation growth is becoming increasingly urgent (Reichstein et al., 2013). However, examining the impact of drought on northern China's vegetation is difficult given the great diversity of landscape and climate. Drought characteristics in terms of magnitude, duration and spatial extent could be quantified by a drought index, allowing observation of water deficit through time and space (Vicente-Serrano et al., 2010). The application of remote sensing data shows great potential to establish the complicated relationship between vegetation vigor and water availability at large temporal and spatial scales (McDowell et al., 2015).

Drought-related damage on vegetation can be characterized by slow growth, low productivity and an increase in plant mortality (Lotsch et al., 2005; McAuliffe and Hamerlynck, 2010; Zhao and Running, 2010). Xu et al. (2012) found that decreased vegetation growth of northern China in the 2000s was associated with an increased frequency of extreme drought. Drought-induced water stress caused a reduction in terrestrial gross primary production over northern China from 1999 to 2011 (Yuan et al., 2014). Liu et al. (2013) indicated that an increase in tree mortality could be expected under future global warming in the semi-arid region of northern China. Nevertheless, the magnitude of the response of vegetation to drought remains uncertain due to drought complexity and intrinsic drought sensitivity among vegetation types (Smith, 2011). The intensity, duration and timing of drought partly determine the effect of drought on vegetation productivity (Ruppert et al., 2015; Zeiter et al., 2016). In the eastern region of northern China, moderate drought with higher temperatures might increase net primary production (NPP), while severe drought caused a delayed response of NPP to precipitation (Sun et al., 2016). Lei et al. (2015) provided evidence that NPP reduction increased along a drought gradient in Inner Mongolia grasslands of China. The capacity for resistance and resilience of land biomes to drought stress changes in different ecosystem types (West et al., 2012; Craine et al., 2013) and environmental conditions such as climatic and edaphic factors (Vicente-Serrano et al., 2013; Gouveia et al., 2017). The vegetation in arid and semi-arid environments chronically exposed to water limitations shows high resistance to drought as well as great resilience when drought conditions end due to its morphological and phenological strategies (Knapp et al., 2015). Grasslands were most responsive to precipitation deficit, followed by forests and deserts in the arid region of northern China (Xu and Wang, 2016). Hua et al. (2017) suggested that the vegetation activity in the eastern region of northern China was more responsive to drought than that in the western region, even in areas with the same land cover type.

Despite an increasing recognition of the negative effects of drought on natural ecosystems and food security (Barriopedro et al., 2012; Yuan et al., 2014; Zhang et al., 2016), few studies have focused on the way by which drought determines vegetation activity across climate zones and land biomes in northern China. Previous studies indicated that vegetation types had different resistance to drought (Wang et al., 2017), and there were diverse vegetation responses to drought in different regions over northern China (Hua et al., 2017). Moreover, the study into the lag effect of drought on vegetation productivity and the vegetation responses to drought at various time-scales is scarce in northern China (Li et al., 2015; Zhang et al., 2017). The concept of drought time-scale refers to the time lag between drought occurrence and its consequences (Vicente-Serrano et al., 2013). The Standardized Precipitation Evapotranspiration Index (SPEI) is a widely used multi-scalar drought index based on meteorological data that quantifies different drought types, and captures the impact of increased temperature on evaporation (Begueria et al., 2010). The satellite-derived Normalized Difference Vegetation Index (NDVI) is considered a robust indicator for vegetation greenness and vigor at regional and continental scales (Carlson and Ripley, 1997).

The present work analyzed the relationship between NDVI and SPEI in northern China, across different climate regimes and land cover types, and determined the drought time-scales at which different ecosystem types respond to persistent water deficit. The objective of this study was to examine the drought responses and the drought resistance of northern China's vegetation by using remote sensing data. As future drought will be more intense and greater in spatial extent during the 21 st century (Wang and Chen, 2014; Leng et al., 2015), this research identifies the most susceptible ecosystem types to meteorological drought and thus supports drought mitigation to reduce land degradation (Wilhite et al., 2007).

2. Materials and methods

2.1. Study area

Northern China spans 31°23′ N–53°34′ N in latitude and 73°29′ E–135°04′ E in longitude, with an area of approximately $5.62 \times 10^6\ \text{km}^2$ (almost 58% of China's total land area). It comprises Northeast China, North China and Northwest China, covering 15 provincial administrative units (Fig. 1a). From the east to the west, elevation increases from the North China and Northeast Plains to the Inner Mongolian, Loess and Qinghai Plateaus. Temperature and precipitation have a gradient from east to west part and from basins to mountains mainly due to regional differences by longitude and topography (Li et al., 2016). By classification criteria of temperature zone and arid/humid region (Zheng et al., 2013), northern China can be divided into 18 climatic sub-regions under the scheme of climate regionalization for the period of 1981–2010 (Fig. 1b). Rich climate diversity contributes to a variety of vegetation communities and soil types. Grasslands and deserts are major land cover types (Xu and Wang, 2016). In this region, the desert is composed of sparse vegetation and closed to open shrubs. Deserts and grasslands dominate most of arid and semi-arid lands. Croplands are located in main parts of Northeast China and North China, and in the eastern portion of Northwest China (Deng et al., 2006). Natural forests are distributed mainly in the Changbai, Greater/Lesser Khingan and Qinling Mountains (Liu et al., 2013). Wide-spread desert and agro-pastoral ecotone are the most serious areas in northern China that suffer from sandstorms (Zou and Zhai, 2004). To reduce and combat sandstorms, the Chinese government has launched many ecological restoration projects since the 1980s (Lu et al., 2015). The vegetation in the desertified areas of northern China still has a weak self-regulation capacity and poor stability at the present time (Wang et al., 2015). Accordingly, increased drought risk may have significant impacts on vegetation establishment and recovery.

2.2. Data sources and preprocessing

To observe inter-annual variations of vegetation activity, we used the third-generation NDVI (NDVI3g) data derived from the Advanced Very High Resolution Radiometer (AVHRR) sensor by the Global Inventory Modeling and Mapping Studies (GIMMS) group. This dataset was provided by the Ecological Forecasting Lab at NASA Ames Research Center (http://ecocast.arc.nasa.gov/). Currently, it has proven to be the best NDVI product for the monitoring of long-term vegetation dynamics in arid and semi-arid lands (Beck et al., 2011; Tian et al., 2015). The GIMMS NDVI3g dataset is a global bimonthly composite product that spans from July 1981 to December 2014 with a spatial resolution of 8 km. It has been corrected for orbital drift, sensor calibration, viewing geometry, volcanic aerosols, atmospheric water vapor and cloud cover, and other errors unrelated to vegetation change (Zeng et al., 2013; Pinzon and Tucker, 2014). To further reduce the effects of cloud and