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Diverse responses of different structured forest to drought in Southwest China through remotely sensed data

Peipei Xu[a,b,c], Tao Zhou[a,b,c,*], Xiang Zhao[a,d], Hui Luo[a,b,c], Shan Gao[a,b,c], Zheng Li[a,b,c], Leyao Cao[a,b,c]

[a] State Key Laboratory of Earth Surface Processes and Resource Ecology, Faculty of Geographical Science, Beijing Normal University, Beijing 100875, China
[b] Academy of Disaster Reduction and Emergency Management, Ministry of Civil Affairs & Ministry of Education, Beijing 100875, China
[c] Key Laboratory of Environmental Change and Natural Disaster, Ministry of Education, Beijing Normal University, Beijing 100875, China
[d] State Key Laboratory of Remote Sensing Science, Jointly Sponsored by Beijing Normal University and Institute of Remote Sensing and Digital Earth of Chinese Academy of Sciences, Beijing 100875, China

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ABSTRACT

Global climate change leads to gradual increases in the frequency, intensity, and duration of extreme drought events. Human activities such as afforestation and deforestation have led to spatial variation in forest structure, causing forests to exhibit an age-spatial structure relationship. Thus, it is of great importance to accurately evaluate the effects of drought stress on forest ecosystems with different forest age structures. Because the spatial heterogeneity varies with drought stress intensity, forest age, there are still a lot of uncertainties in current studies. In this study, based on the field measurement, and the proxy index of stand age (based on forest canopy height from LiDAR and stock volume from inventory) at the regional scale, we analyzed the different drought responses of forest ecosystems with various forest ages across different scales in Yunnan province, southwest China from 2001 to 2014. At the local scale, significant differences in the effects of drought stress were found among forests with various ages, suggesting that older forests suffer more under drought stress than younger forests. At the regional scale, the investigation statistics of forest damage indicated a maximum damage ratio in the forest with tall trees (> 32 m), whereas damage was minimal in the forest with short trees (< 25 m). The stock volume of the forest exhibited the same pattern, that is, the forest damage ratio increased as the stock volume increased. These data demonstrate that the responses of forest drought could be affected by forest age. Under drought stress, older forests show greater vulnerability and risk of damage, which will require special attention for forest managers, as well as improved risk assessments, in the context of future climate change.

1. Introduction

In the context of global climate change, the frequency, intensity, and duration of drought stress have gradually increased (Cook et al., 2014), which substantially impact the structure and function of forest ecosystems (Choat et al., 2012). Drought not only affects the vigor and growth of trees, but also induces tree death and forest degradation (Choat et al., 2012). The effects of drought on forest ecosystems are multifaceted, and can include decreases in forest productivity (Ciais et al., 2005) and advancement of the dormant period (Xie et al., 2015). Accordingly, trees respond to drought stress by adjusting the growth of their root systems, and by reducing stomatal conductance and leaf area (Nepstad et al., 1994; Delzon and Loustau, 2005; Niu et al., 2014). Forest ecosystem responses to drought and their internal adjusting mechanisms vary according to drought intensity and duration (Niu et al., 2014), which add to the uncertainty of forest responses to drought (Guarín and Taylor, 2005; Nepstad et al., 2007). In addition, human activities such as deforestation and afforestation also increase the variation in forest attributes such as forest age structure. Therefore, to better mitigate and adapt to the impact of human activities and climate change on forest ecosystems, a more accurate evaluation of drought stress in forests with different attributes (such as forest age) is required (Piao et al., 2011; Steinkamp and Hickler, 2015).

Lack of rainfall is the primary cause of droughts, and precipitation is the most direct index for analyzing the characteristics of drought. When evaluating the intensity of drought, multiple indexes for drought assessment have been constructed using precipitation and temperature data. The Standardized Precipitation Index (SPI), mainly based on

Abbreviations: EVI, enhanced vegetation index; ED, EVI deficit

* Corresponding author at: Beijing Normal University, No. 19, XinJieKouWai St, HaiDian District, Beijing 100875, China.
E-mail address: tzhou@bnu.edu.cn (T. Zhou).

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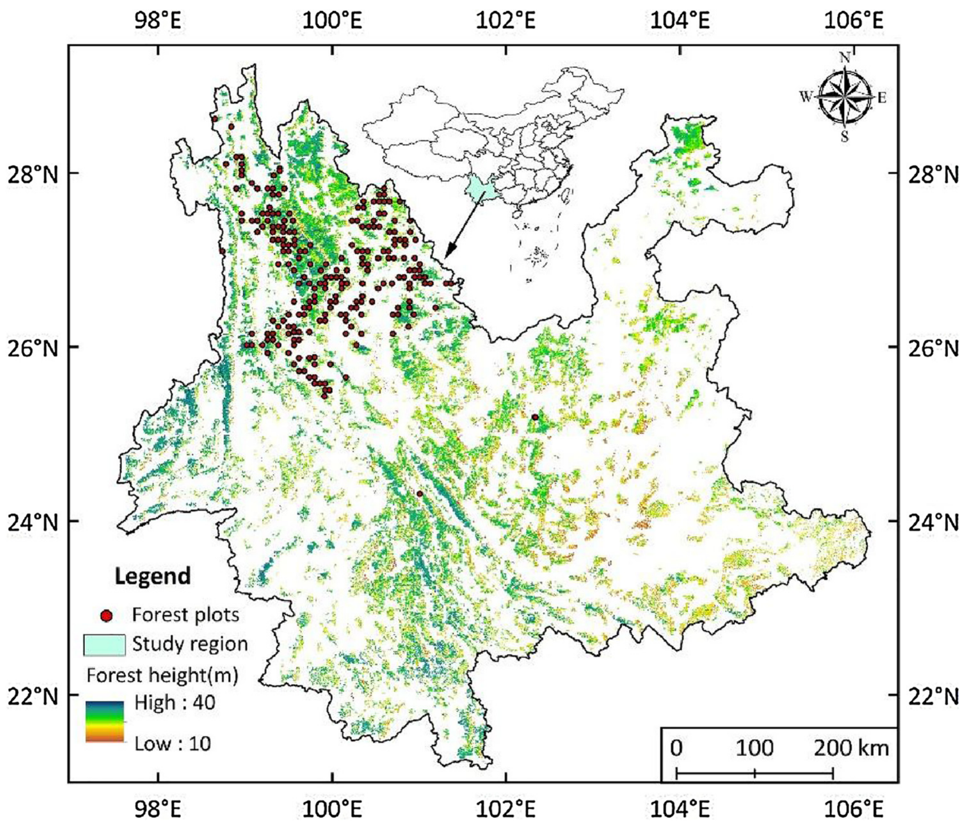

Fig. 1. The spatial location and the distribution pattern of forests in the study region. The forest distribution was obtained from the 7th Inventory of National Forest Resources (State Forestry Administration, 2010a), forest height was from Simard et al. (2011) and the field measurement of forest age was as described in Guo and Ren (2014).

precipitation data, is easy to calculate and can be utilized to indicate drought at different time scales (McKee et al., 1993). Without precipitation, the temperature increases which leads to water evaporation, aggravating the drought intensity (Sheffield and Wood, 2008). Therefore, the drought indexes that contain temperature information, such as Palmer Drought Severity Index (PDSI) and standardized precipitation evapotranspiration index (SPEI), are more useful for analyzing drought characteristics (Sheffield and Wood, 2008). Due to the time hysteresis (Wu et al., 2015) and the accumulative effect (Huang et al., 2015) of climate responses in plants, it is necessary to apply a meteorological index at multiple time scales for drought evaluation (Li et al., 2015; Huang et al., 2015; Luo et al., 2016). As SPEI integrates both the advantages of PDSI (where the effect of temperature trends and fluctuations in evaporation are considered) and SPI (which is easy to calculate and multiple time scales are considered), it is widely used at global and regional scales (Vicente-Serrano et al., 2010).

The differences in forest attributes constitute another important reason that forests differ in their responses to drought. The age of forests, age-related tree height, and stock volume all significantly affect the water absorption and consumption of trees. Previous research demonstrated that soil water was less available to small trees with shallow roots compared to its availability to large trees with developed root systems, thereby making small trees more sensitive to drought stress (Guarín and Taylor, 2005; Nakagawa et al., 2000). Other studies have revealed that water transportation paths are longer in large trees, that their consumption is higher to maintain respiration, and that evapotranspiration on the leaf surface is more vigorous in large trees, which leads to a higher water demand; thus, drought would appear to have a greater impact on large trees (Nepstad et al., 2007). The forest age is an important reference index in all the attribute factors influencing forest water balance. According to the growth theory of trees, diameter at breast height (DBH), tree height, and stock volume are all related to forest age (Zhang et al., 2014), and these factors are reflected in the photosynthetic and productive activity of forests (Zhou et al., 2013; Zhou et al., 2015). Human activity (such as afforestation) is a significant driving factor in changes to forest age, so revealing the differences in drought responses of forests with various forest ages may facilitate better management to control forest damage risk in future climate change. At the regional scale, the drought response of forest can be affected by the spatial heterogeneity of the meteorological drought index and the intrinsic forest attributes. Thus, the influence of spatial heterogeneity for meteorological drought should be removed to reveal the effect of vegetation attributes (such as forest age) on the response to drought stress (Luo et al., 2016).

Remote sensing technology, which is a high-efficiency modern data acquisition tool, could provide data with high spatial and temporal resolution for forestry research (Assal et al., 2016; Dorman et al., 2013; Xie et al., 2015). The optical properties of green vegetation, which shows strong absorption in the red wave band and strong reflectance in the near infrared wave band, allows for easy calculations of metrics to identify changes in vegetation. Multispectral sensors mounted on different satellites provide a wealth of reflectivity data for studies on the earth's surface. For example, the moderate-resolution imaging spectroradiometer (MODIS), mounted on the satellites of Terra and Aqua, supplies data for various vegetation indices based on the calculation of remote-sensing reflectance, which is widely used in the study of ecology. Of these, the most commonly used index is the normalized difference vegetation index (NDVI) and enhanced vegetation index (EVI). Compared with NDVI, EVI is more adapted to study areas with high vegetation coverage at the regional scale (Matsushita et al., 2007). Trees respond to drought stress by reduce leaf area (Nepstad et al., 1994), which could be reflected in the information from satellite observation (Huang et al., 2015).

In this study, by integrating field measurement data, remote sensing data, national forest inventory data, and climate data, we analyzed the drought responses in different forests with various forest ages, stock volumes, and canopy height at local and regional scales to reveal different drought responses in forests of different forest ages. The objectives of this study are to solve two scientific questions: Eliminating the interference of spatial heterogeneity, 1) do differences in forest age