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Response of vegetation to water balance conditions at different time scales across the karst area of southwestern China—A remote sensing approach

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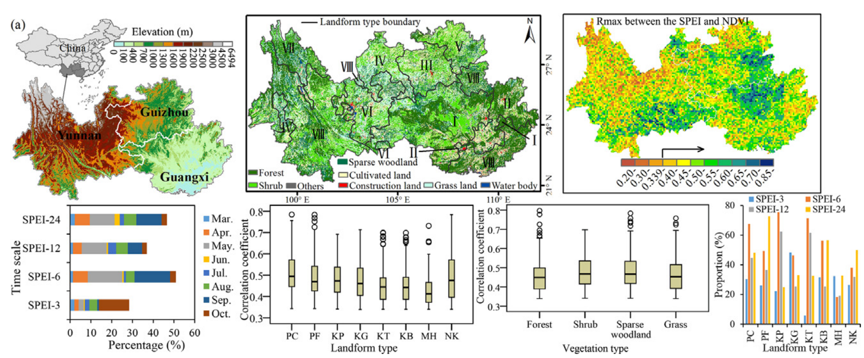
HIGHLIGHTS

- Standardized Precipitation and Evapotranspiration Index (SPEI) were applied in karst area.
- Water imbalance impacts on vegetation were analyzed.
- The vegetation communities and landform types where vegetation growth is most sensitive to water imbalance were identified.

GRAPHICAL ABSTRACT



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ABSTRACT

This work identifies the vegetation communities, landform types and seasons in which vegetation is most sensitive to water imbalance in the karst area of southwestern China. The normalized difference vegetation index (NDVI) and standardized precipitation and evapotranspiration index (SPEI) were used to evaluate the effects of water balance conditions on vegetation in different seasons and at different time scales. During the growing seasons from 1982 to 2013, the vegetation growth in 79% of the study area was statistically significantly sensitive to the water balance condition ($p < 0.05$). The vegetation in the spring and autumn responded more visibly to water imbalances. The SPEI over the last 6 months was statistically significantly correlated with the monthly maximum NDVI during the growing season over the larger areas compared with the SPEI over other time periods. Therefore, the vegetation was most likely sensitive to six months of water imbalance in this area. Among the selected vegetation types, the shrubland and sparse woodland were the most sensitive to water imbalances, whereas grasslands and forests were less sensitive. The maximum correlation coefficient between the NDVI and SPEI for each karst landform type was statistically significantly different ($p < 0.01$). The vegetation in the peak-cluster depressions was the most sensitive to water imbalances, whereas the vegetation in the middle and high karst mountains was the least sensitive to water imbalances. Overall, although the climate of the karst region of southwestern China is humid and subtropical, the vegetation is still vulnerable to water imbalances in particular regions and soils.

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1. Introduction

Climate change can have a significant impact on the structure, function, growth and yield of plant communities (Bradley et al., 2010; Reddy et al., 2004; Zhang et al., 2013a; Bayat et al., 2016). For example, increased carbon dioxide concentrations and extreme climatic events directly or indirectly affect vegetation growth (Sorte et al., 2013). The intensity and frequency of extreme precipitation events such as droughts will likely increase in the future (Manea et al., 2016; Wu et al., 2018). The reduced availability of soil water due to increasingly poor water balance is an important limiting factor for plant growth, and the frequency of the occurrence of such conditions may increase (Silberstein et al., 1999). Currently, drought is the natural disaster causing the greatest decrease in crop yields and has significant negative impacts on ecological environments, societies and economies worldwide (Hayes et al., 2012a, 2012b; Mishra and Singh, 2010). Due to droughts, crop yields in China have been annually reduced by 15–25 million tons, accounting for 4–8% of the national crop production and approximately 55% of the annual reduction in crop yields due to natural disasters in China (Qin et al., 2014). The 2009 drought event in northern China affected 157 million acres of arable land. An extreme drought event in 2009–2010 in southwestern China caused 120 million acres of food production losses (Zhao et al., 2017). Therefore, assessment of the response of vegetation to water balance conditions could be an effective contribution to the evaluation of the capacity of the environment to sensitive to climate changes.

During the past decades, considerable attention has been given to the frequency, intensity, spatiotemporal distribution and influencing factors of water imbalance. Based on this information, many water balance (or drought) indices have been proposed for quantitative analysis and evaluation (Zhai et al., 2010; Belayneh et al., 2014; Zhang et al., 2013b; Beguería et al., 2014; Zhou et al., 2016). Currently, there are many widely used water balance (or drought) indices, including the Palmer drought severity index (PDSI) (Palmer, 1965; Heim, 2002), the self-calibrating PDSI (SC-PDSI) (Wells et al., 2004), the standardized precipitation index (SPI) (McKee et al., 1993, 1995; Hayes et al., 1999), and the standardized precipitation evapotranspiration index (SPEI) (Vicente-Serrano et al., 2010). The SPEI considers two important water balance factors, precipitation and evapotranspiration. In addition, this index also applies to different time scales of water balance conditions and is one of the most widely used water balance (or drought) indices for evaluating, monitoring, and assessing water balance conditions under global warming (Heim, 2002; Yu et al., 2014; Hernandez and Uddameri, 2014; Tong et al., 2017).

By applying water balance indices, many studies have analyzed the response of vegetation to water balance conditions at different time scales and in different regions (Tan et al., 2015; Lou et al., 2017) and have provided robust literature on vegetation responses to water imbalance. For example, the spatiotemporal variation in negative water balances in China and its impacts on agriculture during 1982–2011 have been analyzed using the PDSI indices and agriculture drought survey data (Yan et al., 2016). By utilizing the SPEI and the normalized difference vegetation index (NDVI), Zhao et al. (2018) evaluated the response of vegetation productivity to different time scales of water imbalance on the Loess Plateau, China. With the third-generation NDVI (GIMMS AVHRR NDVI3g) and SPEI, the relationships between vegetation and water imbalance were investigated in northern China (Hua et al., 2017). With the purpose of determining the vegetation communities, regions and seasons in which vegetation changes are driven by negative water balances, Gouveia et al. (2016) analyzed the water imbalance impacts on vegetation across the entire Mediterranean basin. The above studies, although using different methods and data, have provided a robust literature on vegetation responses to water imbalance.

Karst is defined by the geological substrate: limestone or dolomite bedrock. The karst area of southwestern China has a population of 100 million people. This region is characterized by a complex network of soil pockets, rock matrices, and flow paths with variable hydraulic conductivity (Fu et al., 2015; Li et al., 2016). Compared with other karst regions around the world, such as the Mediterranean karst region and the karstic Edwards Plateau, this landscape is especially rugged, with average terrain slopes over 20%. Under these geological conditions, severe soil erosion leads to large rock outcropping (Wang et al., 2004; Zhang et al., 2014), and different rock porosity types lead to substantial complexities in surface and subsurface water movement features (Bakalowicz, 2005; Jones et al., 2000). The karst-related characteristics of water movement, such as a higher percolation rate, faster groundwater flow through karst conduits, and reduced soil depth, result in rapid water infiltration into the deep subsurface, thus rendering the water inaccessible to plants at the surface (Fleury et al., 2013; Hao et al., 2012; Zhang et al., 2011). Thus, although southwestern China has a subtropical humid climate, this region often suffers from severe water imbalance.

To date, many scientists have studied the relationship between vegetation growth and water balance in the karst area of southwestern China (Lian et al., 2015; Wan et al., 2016). Most studies have focused on the water stress resistance of specific plant species. For example, Liu et al. (2012a, 2012b) assessed the drought tolerance of a plant used to revegetate heterogeneous karst landscapes in southwestern China. Zhang et al. (2017b) analyzed the responses of the antioxidant defense system of epilithic mosses to water stress in karstic rocky desert areas. However, there is little information on the regional vegetation responses to water balance changes in the karst area.

In the karst area of southwestern China, water balance conditions are important factors influencing vegetation growth and should be reflected in variation in NDVI. In this context, the impacts of water balance conditions on vegetation growth in the karst area of southwestern China were analyzed to determine the most sensitive vegetation communities and landform types. We also aimed to determine the corresponding time scales of water balance conditions that are more likely to have negative or positive effects on vegetation. Over the period from 1982 to 2013, the SPEI was assessed for each month over a range of time scales (3, 6, 12 and 24 preceding months). The monthly maximum NDVI from the Global Inventor Modeling and Mapping Studies (GIMMS) NDVI3g dataset served as a proxy for vegetation growth. Pearson correlations between the SPEI at different time scales and the NDVI values were evaluated.

2. Materials and methods

2.1. Study area

In this analysis, the study area that included the karst region of southwestern China extended to Yunnan and Guizhou Provinces and the Guangxi Zhuang Autonomous Region of China (97.5–112°E, 21.1–29.2°N) and covered an area of 796,773 km^2 (Fig. 1a). The dominant lithology this region is limestone and dolomite, and the main soil types are Haplic Alisols (common topsoil fractions: 40% sand, silt 37% silt, clay 23% clay), Chromic Luvisols (topsoil fractions 27% sand, 27% silt, 46% clay), Rendzic Leptosols (topsoil fractions: 37% sand, 44% silt, 19% clay) and Dystric Regosols (topsoil fractions: 42% sand, 37% silt, 21% clay). This region features a subtropical humid monsoon climate. Because of numerous fissures and conduit networks in the bedrock, a large amount of surface water infiltrates into underground rivers, forming the surface and two underground hydrological systems. The study area has a mean annual temperature of 17.6 °C and a mean annual precipitation of 1021 mm (Fig. 1c, d). The precipitation from April to October accounts for 75–85% of the annual precipitation. Spatially, the central and northern parts of Yunnan receive less precipitation, with an annual average of approximately 900 mm, whereas Guangxi receives more precipitation, with an annual average of over 1500 mm (and approximately 1200 mm in Guizhou). The landscape heterogeneity is striking in this area, where the elevation decreases from the Yunnan Plateau (up to 4000 m a.s.l.) in the northwest to the Xunjiang Plain