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Original Articles

Spatiotemporal variation in vegetation coverage and its response to climatic factors in the Red River Basin, China

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ABSTRACT

Vegetation coverage is a critical factor in soil conservation and improving the ecological environment. As an important ecological corridor connecting China's southwest and Southeast Asia, the Red River Basin is characterized by vulnerable ecosystems and serious soil erosion. Identifying the heterogeneity in vegetation coverage and its response to climatic factors are critical for ecological protection and soil and water conservation. MOD13Q1 NDVI data with a spatial resolution of 250 m and 16 d temporal resolution were collected from 2000 to 2014. The maximum synthesis method, univariate linear regression, Hurst exponent, and partial correlation analysis were used to detect the spatiotemporal variation and sustainability of vegetation coverage and characterize the relationship between vegetation NDVI and climatic factors in the wet season in the Red River Basin. NDVI showed a rather significant increasing trend in the wet season. The "corridor-barrier" function of valleys and mountains affected the spatiotemporal patterns in the Longitudinal Range-Gorge Region. Areas of improved, degraded, and stable vegetation coverage accounted for 50.1%, 27.1%, and 22.8% of the total, respectively. The role of precipitation was higher than temperature in the interaction between NDVI and climatic factors. A time lag effect was found in the NDVI response to rainfall and temperature variation. Different vegetation types showed various spatiotemporal responses to climatic factors. Human activities, especially the implementation of the Grain for Green Project (GFGP), affected the spatial and temporal patterns of vegetation coverage.

1. Introduction

Vegetation plays an essential role in regional and global ecosystem stability. The change in terrestrial net carbon uptake is principally affected by varying vegetation productivity (Ciais et al., 2005; Peylin et al., 2005; Schwalm et al., 2010), and the Earth's climate is regulated by vegetation through evapotranspiration, surface albedo, and roughness (Jackson et al., 2008; Anderson et al., 2011). Furthermore, vegetation coverage is a critical factor in soil conservation and improving the ecological environment (Cyr et al., 1995; Hupy, 2004; Zhou et al., 2006). The Normalized Difference Vegetation Index (NDVI) is functionally correlated with vegetation coverage (Baret and Guyot, 1991). It can reflect vegetation parameters, including the absorption of photosynthetically active radiation, chlorophyll density, leaf area, and evaporation rate (Defries et al., 1995). It is very sensitive to variations in vegetation growth and also acts as an effective index for studying the vegetation response to climate change (Linderholm, 2006). Therefore, the NDVI has been widely used to analyze vegetation cover (Yang and Piao, 2006), vegetation health (De Keersmaecker et al., 2015), plant production (Zhang et al., 2014), and phenology (Jenkins et al., 2002; Piao et al., 2006a; Yu et al., 2010; Cong et al., 2013).

As global climate has changed, quantitative studies on the relationship between vegetation and climate have become crucial at both regional and global scales (Li et al., 2011; Chuai et al., 2013; Gonsamo et al., 2016). Vegetation is rather sensitive to environmental changes, and climate is the most important natural driving force that has a decisive effect on vegetation growth (Piao et al., 2011). The response of the vegetation coverage to climate change in the wet season is the most sensitive and this relationship has been widely studied (Zhang et al., 2013a; Zeng et al., 2013; Ge et al., 2017). Vegetation at mid-high latitudes in the northern hemisphere has been strongly affected by temperatures as global temperatures have risen significantly over the past few decades (Sun et al., 1998). Piao et al. (2006b) found that the growing season has lengthened due to global warming at the northern high latitudes in recent decades. The effect of temperature on vegetation is rather complex. Studies have shown that temperature had a negative correlation with vegetation in the Qinghai-Tibet Plateau (Dong et al., 2013). However, other studies have suggested that an

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increase in temperature is beneficial to vegetation growth (Chen et al., 2010; Kang et al., 2011). The primary reason for the inconsistency is a significant difference in the response of vegetation in areas with varying dry-wet conditions and differing types of vegetation with temperature (Li et al., 2011). Nevertheless, under the influence of the greenhouse effect, the temperature is no longer a limiting factor for vegetation growth in temperate regions. The sensitivity of vegetation growth to climate change will be gradually reduced accordingly (Piao et al., 2006b). Furthermore, as increasing temperature may easily lead to drought, the vegetation response to temperature is also slowly weakened. With global warming, precipitation has also significantly changed. Few researchers have focused on the relationship between vegetation and precipitation (Fang et al., 2005), although it is generally positive, i.e., NDVI increases with precipitation increases and vegetation grows well. The situation is particularly evident in semi-arid areas (Ichii et al., 2002). The response of different plant communities to precipitation is inconsistent. With increasing precipitation, grassland NDVI and broad-leaf forests increase significantly, while NDVI decreases. This relationship is generally found in humid areas or alpine regions (Chen et al., 2010). Moreover, vegetation growth is also related to the duration and frequency of precipitation (Sun et al., 2001). Fay et al. (2003) reported that vegetation productivity decreased due to decreasing precipitation frequency in the case of constant precipitation. Previous studies have indicated that there is a time lag effect in the NDVI response to climatic factors (Wang et al., 2003; Liu et al., 2013; Zhou et al., 2014). There is no doubt that the relationship between NDVI and climatic factors has significant temporal and spatial heterogeneity.

Global warming has clearly progressed over the 50 years, while precipitation has fluctuated. The response to climate change is particularly evident in alpine vegetation (Keller et al., 2000). Moreover, variations in vegetation with elevation in mountainous areas is obvious, with diverse vegetation types. Due to the impact of global warming, precipitation and temperature in southwest China has undergone a more significant change since 2000. Furthermore, climate change has led to an increase in extreme weather events (Li et al., 2015). One important ecological corridor connecting China's southwest and Southeast Asia is the Red River Basin, located in the Longitudinal Range-Gorge Region (He et al., 2005). As an important international river, Red River covers China, Vietnam and Laos. The Red River Basin is characterized by spatially different climatic conditions, complex and diverse geomorphological features and rich vegetation species. The ecological environment in this district is fragile and sensitive to global climate change. Thus, it is a typical area for studying global environmental evolution. Soil erosion, runoff and sediment variation, ecological security, eco-environment protect and construct have been the focus of many studies in the region (Le et al., 2010; Duan et al., 2016; Li et al., 2013). Ignoring these issues will pose a huge threat to river health, food security, and hydropower energy development in downstream countries. The relationship between vegetation coverage and climatic factors in Red River Basin can be used to scientifically predict and address the impact of climate change. In addition, it can also provide a scientific basis for such issues as the maintenance of transboundary eco-security, the conservation of regional biodiversity, the use of water resources, and geopolitics. Therefore, the research topic of this paper has its own necessity and urgency. Li and He (2009) evaluated the ecological effects of the “corridor-barrier” function of valleys and mountains to the spatial-temporal variation in NDVI, and its relationships to climatic factors in the Red River Basin from 1981 to 2006. The results showed that vegetation had no significant increasing trends and there was a time lag effect in precipitation and temperature variations. Zhang et al. (2011) found that climate change, especially the rise of annual average temperature, was the key reason for NDVI changes for 1982–2006 in the Red River Basin. Concurrently, the implementation of the Grain for Green Project (GFGP) has provided ecological and economic benefits. Few studies have detected the relationship between NDVI and climatic factors in the last dozen years or so. Different data sources and time scales may produce various research results. The spatial and temporal resolution of remote sensing data that most of the existing studies have adopted are relatively coarse. These studies focused on the impact of natural factors on vegetation coverage, and more or less ignored the influence of human activities. Thus, this paper explored the variation of vegetation coverage from the aspects of climatic factors, topography and human activities. Besides, the precipitation and temperature variations in Southwest China were rather unusual compared to the past, especially millions of residents were threatened by shortage of drinking water and bared farmland because of the large-scale drought disaster from November 2009 to March 2010 (Mao et al., 2010; Wang et al., 2011). Against this backdrop, what about the relationship between vegetation coverage and climate change? This is one of the focuses of this study. Furthermore, the spatial resolution of NDVI is higher than the preexisting studies. In addition, precipitation is mainly concentrated in the wet season, from mid-April to the end of October, with a higher risk of soil erosion (Gu et al., 2016). The wet season in this basin has always been the essential time period in eco-environment protect and construct.

The variation in vegetation NDVI and its response to climate factors over the recent 15 years have been poorly studied. At present, data with combined high spatial, temporal, and spectral resolutions is convenient to obtain. However, the application of MODIS 250 m time series data for long-term dynamics detection of vegetation coverage in the wet season has been limited. The inter-annual trends in vegetation and quantitative evaluation of vegetation NDVI still remains uncertain. Furthermore, few of studies on vegetation NDVI in the Red River Basin have focused on future trends due to the difficulty in simulating vegetation trends through mathematical models. With the availability of data and progress in statistical analysis methods, it is possible to better understand and evaluate changes in vegetation cover and its relationship with climate. Besides, these techniques can specifically target the response of vegetation to climate change in alpine areas to vegetation productivity and the carbon cycle in mountain ecosystems. Understanding the climate-driven mechanism of vegetation NDVI can provide a scientific basis for addressing the impacts of climate change.

In this study, the MOD13Q1 NDVI images with a temporal resolution of 16 days and spatial resolution of 250 m were collected from 2000 to 2014. The MOD13Q1 data were pre-processed and calculated to obtain the annual wet season NDVI time series for 2000–2014. Linear regression analysis and the Hurst exponent method were used to detect spatiotemporal patterns and sustainability of vegetation coverage in the Red River Basin. Climate data sets, including daily precipitation and temperature, were obtained from 23 meteorological stations in the study area. The objectives were to a) detect the spatiotemporal variation and sustainability of vegetation coverage in the Red River Basin and b) identify the relationship between vegetation NDVI and climatic factors in the wet season for the 2000–2014 period.

2. Methods and datasets

2.1. Study area

The Red River Basin is located within the Longitudinal Range-Gorge Region of Southwest China (Fig. 1). The Red River is an important international river in China and Southeast Asia, flowing through China, Vietnam, and Laos. The watershed area is about 7.4×10^4 km^2, with a 677.0 km mainstream in China. The study area shows a “meniscus shape” in China between 22°27′–25°32′ north and 100°06′–105°40′east. The mean altitude above sea level is 1529 m, with elevations varying between 76 and 3200 m. The geomorphology of the study area is divided into two units: the Yunnan Plateau, in the east, and Hengduan mountain, in the west, with the Red River Valley in the middle. There are two parallel mountain systems, the Ailao and Wuliang mountains, in a northwest-southeast direction in the west. The majority of the basin