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Research paper

Spatiotemporal variation of vegetation coverage before and after implementation of Grain for Green Program in Loess Plateau, China

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ABSTRACT

Ecological restoration is an effective method for mitigating environmental degradation, controlling water loss, and diminishing soil erosion. Long-term ecological restoration projects are critical for sustainable regional economic and ecological development. To understand the ecological transition from 1982 to 2013 in the Loess Plateau (LP), this study analyzed the spatiotemporal variability of vegetation using the satellite-derived Normalized Difference Vegetation Index (NDVI) dataset, known as the third-generation Global Inventory Modeling and Mapping Studies (GIMMS3g) dataset. Furthermore, the relationships between NDVI, climate change, and the "Grain for Green" Program (GGP) were assessed. At the regional scale, the average growing season, spring, summer, and autumn NDVI showed a significant increase from 1982 to 2013, 1982 to 1999, and 2000 to 2013, most notably in the latter period. At the pixel scale, the average growing season, spring, summer, and autumn NDVI decreased from the southeast to the northwest LP during the three time periods. In most areas in the LP, this parameter increased during the three periods, especially in 2000–2013. Moreover, increasing precipitation resulted in an improvement in vegetation cover. The average NDVI in the growing season was positively (negatively) correlated with precipitation in the north (south) LP during 1982–2013. In terms of human activity, our results indicate a strong correlation between the cumulative afforestation area and NDVI for 1998–2013, with $r = 0.73$, $n = 16$, and $P < 0.001$.

1. Introduction

Vegetation is one of the most critical elements of terrestrial ecosystems and plays an important role in material cycling and energy flow (Peng et al., 2011; Sun et al., 2015). Spatiotemporal variations in vegetation growth can affect the terrestrial carbon cycle and other biochemical processes (Piao et al., 2011). In recent decades, land degradation, soil erosion, water pollution, and other environmental problems have become increasingly severe in many parts of China, influencing its agricultural production as well as economic and social sustainability (Yang et al., 2005). The major causes are overgrazing and excessive reclamation of vegetation for short-term agricultural and economic development. This is especially true in the steep slopes of arid and semi-arid regions, and has resulted in increased river sediment transport and a high risk of flooding (Maeda et al., 2010; Wang et al., 2016). In order to minimize these problems, the Chinese government implemented a nationwide ecological recovery program known as the "Grain for Green" Program (GGP) in 1999 (Lü et al., 2015; Xu et al., 2004). The objective of this project is to increase vegetation coverage and control water loss and soil erosion by planting trees and converting cropland or bare land on steep slopes to trees and grasslands. In 1999–2001, approximately 12,000 km^2 of farmland nationwide was converted into grassland or forest (Xu and Cao, 2002). Since 2003, the conversion rate has accelerated, and approximately 70,000 km^2 of farmland and 50,000 km^2 of bare land have been converted into grassland and forest, according to official statistical data (Zhou and Van Rompaey, 2009).

The Loess Plateau (LP), the pilot region of the GGP, is located in the middle reaches of the Yellow River, North China, where vegetation is vulnerable to climate variability and human activities. This area has experienced the most severe vegetation degeneration,

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water loss, and soil erosion in China due to anthropic overgrazing and excessive reclamation of natural vegetation (Chen et al., 2007; Zhao et al., 2013a,b; Li et al., 2015; Sun et al., 2015). Global warming in recent years has exacerbated these issues, leading to a warmer and drier climate and a higher drought frequency in the LP (Zhang et al., 2012; Wang et al., 2012). Water loss and soil erosion are characteristic of the LP, and contributes approximately 90% of the sediments in the Yellow River (Ren and Shi, 1986). This has led to a loss of nutrients and, therefore, lower crop yield and plant productivity (Xiao, 2014). In recent years, many studies using land use/cover data or the multi-temporal normalized difference vegetation index (NDVI) have indicated that vegetation cover has increased in the LP. According to previous studies, the Land Long Term Data Record (LTDR)-NDVI, Moderate Resolution Imaging Spectroradiometer (MODIS)-NDVI, Global Inventory Modeling and Mapping Studies (GIMMS)-NDVI, and Satellite pour l' observation de la Terre VEGETATION (SPOT VGT)-NDVI have been used to analyze spatiotemporal patterns of vegetation in the LP. Their results indicate that, overall, NDVI increased after implementation of the GGP and that climate change and human activities were the main driving forces for vegetation variability in the LP (Xin et al., 2011; Zhang et al., 2013a,b; Xiao, 2014; Sun et al., 2015). Previous long-term studies detecting vegetation changes in the LP have all used NDVI but from different sensors. However, the NDVI values obtained from different sensors and at multiple spatial resolutions are inconsistent (Liu et al., 2015a,b). This often results in significant differences between NDVI values of two years if the data were derived from different NDVI resources (Scheftic et al., 2014). Meanwhile, vegetation responses to climate variability and ecological restoration, as well as spatiotemporal variations within different vegetation types are still poorly understood in terms of the effects of the GGP in this area. Therefore, it is necessary to study the spatiotemporal variation of vegetation coverage in the LP both before and after GGP implementation, as well as the main driving forces by considering the combined effects of climate variability and ecological restoration.

Remote sensing is regarded as an effective method for monitoring vegetation growth at large scales as it provides data of long time series and high spatial resolution (Pettorelli et al., 2012; Hess et al., 1996). Since the launch of Landsat 1 by the National Aeronautics and Space Administration (NASA) in 1972, innumerable satellite images with different specifications and purposes have been acquired over the last four decades. The use of long time series remote sensing data to monitor spatiotemporal variations in vegetation growth is now widely recognized (Sun et al., 2015). The NDVI dataset, which is often used as a proxy for terrestrial vegetation growth, is an important metric of vegetation degradation and ecosystem features (Zhang et al., 2013a,b). Long-term NDVI time series data is a powerful tool for understanding current and past vegetation status and for predicting future variability in vegetation at regional and continental scales (Du et al., 2015; Piao et al., 2011). The GIMMS-NDVI product is considered an ideal dataset for long-term NDVI trend analysis in large-scale areas because this dataset can avoid merging data by different sensors (Du et al., 2015; Beck et al., 2011). The new NDVI dataset, known as the third generation GIMMS (GIMMS3g) dataset released in 2014, is the longest available global sub-monthly time series of NDVI. Covering July 1981–2013, this dataset has demonstrated good quality and can support more detailed analyses of vegetation variability without merging data from different sensors (Sun et al., 2015; Wang et al., 2014).

The aims of this study were (1) to assess the spatiotemporal variations in vegetation cover in the LP from 1982 to 2013, 1982 to 1999, and 2000 to 2013, and (2) to examine the changes in different vegetation types and their responses to regional climate variability and ecological restoration. The results of this study could enhance the current theoretical understanding of vegetation growth and development conditions, provide an assessment of the GGP effects on environmental restoration, and offer a sound basis for future ecological policies in the LP.

2. Material and methods

2.1. Study area

The LP is located in the middle reaches of the Yellow River, North China. It covers approximately 620,000 km^2, extending from 104°54′E to 114°33′E, and from 33°43′N to 41°16′N (Fig. 1). This region has arid and semi-arid climates. The annual average precipitation varies from 200 to 750 mm, with approximately 60% of the precipitation occurring between June and September (Zhang et al., 2013a,b). The average annual temperature ranges from 4.3 °C to 14.3 °C (Guo et al., 2010). The LP is characterized by highly erodible loess layers, the average thickness of which is 100 m. From northwest to southeast, the major soil type changes from eolian sand and sandy loess to typical loess and clayey loess. The dominant vegetation includes agricultural vegetation, artificial forest, rangeland, shrub land, and grassland. The uneven distribution of water resources, climate variability, and intensive human activity has resulted in drought hazards, severe soil erosion and desertification in the LP (Zhang and Liu, 2005).

2.2. Datasets

The GIMMS dataset, composed of Advanced Very High Resolution Radiometer (AVHRR) sensors, is the earliest published dataset and has the widest applications for assessing variations in vegetation cover (Liu et al., 2015a,b). The most recently released NDVI dataset is the third generation GIMMS dataset (GIMMS3g), obtained from the National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) for the period 1982–2013. The spatial resolution of the data is $0.083^\circ \times 0.083^\circ$, and the temporal resolution is 15 days. The GIMMS NDVI3g dataset has been optimized to minimize the effects due to differences in sensor design between the AVHRR/2 and AVHRR/3 instruments, as well as effects from volcanic eruptions (Pinzon and Tucker, 2014). The monthly GIMMS NDVI3g dataset was calculated using the maximum value composite (MVC) technique. The average NDVI in the growing season was defined as the average monthly composite NDVI from April to October. Spring, summer, and autumn NDVI were defined as the average monthly composite NDVI from March to May, June to August, and September to November, respectively. In this study, pixels with a mean average NDVI of <0.1 in the growing season were considered as non-vegetation and were thus excluded.

Meteorological datasets were obtained from the China Meteorological Sharing Service System (http://cdc.cma.gov.cn/). These datasets include monthly mean temperature and monthly precipitation data from 1982 to 2013 from 52 meteorological stations across the study area (Fig. 1). In addition, a vegetation map of the LP was digitized from a 1:1,000,000-scale map of vegetation in China. It was classified into needle-leaf forest, broad-leaved forest, shrub land, cultivated vegetation, steppe, meadow, marshy grassland and desert. In this study, cultivated vegetation, forest (needle-leaf, forest, and broad-leaved forest), grassland (steppe, meadow, and marshy grassland), and shrub land were selected to analyze the trends of various vegetation types.

2.3. Methods

Ordinary least-squares (OLS)-based linear regression analysis and the Mann–Kendall statistical test were used to detect vegetation trends and the significance of each trend in the NDVI time