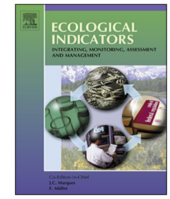
Ecological Indicators 95 (2018) 233–241

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind



Original Articles

Vegetation restoration projects and their influence on runoff and sediment in China

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ARTICLE INFO

Keywords:
Vegetation change
Vegetation coverage
Hurst exponent
Topographical factors
Precipitation

ABSTRACT

The vegetation status in China has undergone obvious changes since vegetation restoration projects were widely implemented in 1999. Based on a statistical analysis and the Hurst exponent index method, the spatial and temporal characteristics of vegetation change and its influence on runoff and sediment in China was analyzed using the Normalized Difference Vegetation Index (NDVI). The results showed that the change of vegetation coverage (E) in China from 2000 to 2015 was 5.64%. There was substantial variation in the spatial distribution of E values. There was a significant increase in the vegetation coverage in the areas covered by five vegetation restoration projects. It was found that 83.34% of the whole of China had experienced a continuous improvement in vegetation coverage. The largest increase in vegetation coverage occurred in the middle of the Loess Plateau and the middle of northeast China, while the largest decrease occurred in some areas of the Qinghai-Tibet Plateau and Xinjiang. Areas of vegetation degradation should be given special attention, with suitable control measures put in place. The slope angle with the largest increase in vegetation coverage was in the range of 15°–25°. Aspect had little effect on vegetation restoration. Vegetation restoration around the Hu Line, in which the precipitation was between 400 and 500 mm, was better and faster than in other regions. Vegetation coverage was linked to annual precipitation, and increased steadily with precipitation until a value of 500 mm was reached, after which it remained stable. Vegetation restoration did not reduce runoff, but it did reduce the sediment concentration. This study provided useful information for decision-makers involved in vegetation restoration projects and environmental management, especially in fragile ecological environments in arid and alpine areas.

1. Introduction

Vegetation plays a vital role in energy exchange, the carbon balance, water and biogeochemical cycles, and the maintenance of climate stability in terrestrial ecosystems (Peng et al., 2012; Fu et al., 2017; Zhang et al., 2018). Because they are sensitive to climate change, vegetation changes are of great significance to the study of global environmental change. Therefore, it is important to monitor the spatial and temporal dynamics of vegetation. The study of vegetation dynamics has become one of the key issues in global change (Fu et al., 2010), and numerous studies of vegetation dynamics have been conducted in different regions of China (Peng et al., 2012; Fang et al., 2013; Fu et al., 2017; Xu et al., 2017; Zhang et al., 2017). The combined effects of climate conditions and human activities affect are more likely to affect terrestrial ecosystems (Esser, 1987; Haberl, 1997; Walther et al., 2002; IPCC, 2007; Du et al., 2015; Zhang et al., 2016; Wu et al., 2017). Topography also can significantly influence vegetation dynamic trends (Peng et al., 2012).

China is divided into three major natural regions: the eastern monsoon region, the northwest arid and semi-arid region, and the Qinghai–Tibet alpine region. The northwest arid and semi-arid region and the Qinghai-Tibet alpine region are both extremely sensitive to climate change. After the flooding of the Yangtze, Nen, and Songhua rivers in 1998, the Chinese government implemented vegetation restoration projects nationwide, with the aim of restoring degraded ecosystem services. The vegetation restoration projects have led to an increase in vegetation coverage in China over the past two decades. Therefore, it is necessary to evaluate the impact of vegetation restoration projects on the spatial and temporal changes and trends of vegetation coverage. Due to its ability to manage high spatial coverage and

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https://doi.org/10.1016/j.ecolind.2018.07.047
Received 1 March 2018; Received in revised form 18 July 2018; Accepted 22 July 2018
1470-160X/

long time series, the normalized difference vegetation index (NDVI) has become an important tool for analyzing the history of vegetation growth, monitoring current conditions, and predicting future changes (Piao et al., 2011; Fensholt et al., 2012). An NDVI dataset is often used to study vegetation change and the distribution of spatial density at large scales (Bai and Dent, 2009; Fensholt et al., 2012; Du et al., 2015; Duan et al., 2016). Many studies have analyzed the vegetation changes and corresponding influencing factors in different regions of China based on NDVI data. For example, Sun et al. (2015) reported that the annual NDVI displayed a slight increasing trend in northern China. Human activities have generally played a positive role in vegetation growth. Nearly 61.2% of the total grassland area in the Qinghai–Tibet Plateau has experienced restoration and 56.7% of the degraded grassland areas were influenced by the climate (Wang et al., 2016). Wang et al. (2015) found that annual vegetation growth in China displayed an increasing trend. Droughts had large negative impacts on vegetation growth, especially in the northwestern area. There were large vulnerable areas of forest vegetation in northeastern and southwestern China (Wan et al., 2017). Although previous studies have provided much information regarding vegetation change and the spatio-temporal distribution pattern of vegetation coverage in different regions, most studies have focused on the driving forces of vegetation dynamics. Few studies have investigated the dynamic trends in vegetation coverage after these studies were completed, especially for the primary watersheds in China. In addition, little work has been conducted to examine the effects of vegetation restoration projects, topography, and precipitation on vegetation restoration status in China. Furthermore, the impact of vegetation restoration on runoff and sediment in China's major rivers has seldom been studied.

Understanding the effects of vegetation restoration projects on vegetation change, runoff, and sediment is vital to building an ecological civilization and restoring key ecosystems to strengthen the quality and stability of the ecosystems in China. Therefore, the objectives of this study were to: (1) analyze the spatio-temporal changes of vegetation coverage and the consistency of vegetation dynamic trends caused by vegetation restoration projects, (2) examine the differences in the vegetation restoration response to precipitation and topography, and (3) evaluate the impact of vegetation restoration projects on runoff and sediment in China's major rivers.

2. Materials and methods

2.1. Vegetation restoration projects in China

To improve the ecological environment and the ecological security of China, in recent decades the Chinese government has implemented vegetation restoration projects to control soil and water loss, reduce floods, protect biodiversity and restore degraded ecosystem services (Fu et al., 2017). The main vegetation restoration projects in China are the Natural Forest Protection Project (NFPP), 'Grain-for-Green' Project (GGP), Three-North and Yangtze River Basin Shelterbelt Forest and other Shelterbelt Forest Project (TYSFP), Timber Forest Base Construction Project (TFBCP), and the Beijing–Tianjin Dust Storms Source Control Project (BDSCP).

The goal of the NFPP is to fundamentally control the deterioration of the ecological environment and to protect biodiversity. The NFPP was officially implemented in 2000 to protect and restore natural forests, and at the time was the largest ecological project in China in terms of direct investment. The NFPP extends over 17 provinces (autonomous regions, municipalities directly under the Central Government) and is divided into the upper reaches of the Yangtze River region, the upper and middle reaches of the Yellow River region, and the key state-owned forest regions in the northeast, Inner Mongolia, Hainan Province, and Xinjiang Uygur Autonomous Region (Fig. 1a).

The goal of the GGP is to restore sloping cropland to forest or grassland to reduce soil erosion and water loss. In 1999, Sichuan, Shaanxi, and Gansu provinces took the lead as pilots for the GGP. The GGP was fully implemented in 2002, and became the most extensive ecological project in China, involving the participation of more individuals than any other such project. The aim was to return all sloping cropland between 15° and 25° in water source areas and sloping cropland above 25° to forest or grassland. The GGP was extended to 25 provinces (autonomous regions, municipalities directly under the Central Government), including a total of 1897 counties (county-level cities, districts, banners: the county is called banner by the Mongolian people) (Fig. 1b). The GGP Project has subsequently become a major ecological project with the largest investment, the strongest policy, the most extensive coverage and the highest participation of people in both China and the world.

The TYSFP includes the Three-North Shelterbelt Forest Project (TSFP); Afforestation in Taihang Mountains Project (ATMP); Yangtze River Basin Shelterbelt Forest Project (YRSFP), Pearl River Basin Shelterbelt Forest Project (PRSFP); and the Coastal Shelterbelt Forest Project (CSFP). The TSFP, ATMP, YRSFP, PRSFP, and CSFP were initiated in 1978, 1994, 1989, 1996 and 1990, respectively. The TYSFP extends over 28 provinces (autonomous regions, municipalities directly under the Central Government), with the aim of restoring and developing water conservation forests, and soil and water conservation forests (Fig. 1c). The TSFP specifically manages the hazards of sandstorms and serious soil erosion and water loss problem in the northwest, north, and northeast of China. The YRSFP and PRSFP were initiated mainly to protect water resources in the Yangtze and Pearl rivers, respectively. The ATMP was established for water conservation, and soil and water conservation in the Taihang Mountains. The aim of the CSFP was to prevent wind erosion and to fix sand, conserve water and soil, and effectively resist natural disasters in China's coastal areas.

The TFBCP was initiated mainly to provide a supply of timber and forest products in China. The aim was to facilitate the change from cutting natural forest to harvesting plantation, which would promote the smooth implementation of vegetation restoration projects. The TFBCP was implemented in 18 provinces (autonomous regions) in 2001 (Fig. 1d). The area covered by the project was east of the 400-mm isohyetal line. The priority area was east of the 600-mm isohyetal line, with good natural conditions, good site conditions, and relatively flat terrain. In this area, plantation forestry was not likely to cause soil erosion and impact on the ecological environment.

The aim of the BDSCP was mainly to solve the problem of sandstorm hazards around Beijing and Tianjin. The BDSCP was implemented in 75 counties (county-level cities, districts, banners) in 2001 (Fig. 1e). The main measures adopted were to protect existing vegetation, restore vegetation in sandy areas, comprehensively control degraded grassland, control soil and water loss, and build water conservation forests in Beijing and the surrounding area.

2.2. Data preparation

A digital elevation model (DEM) for China was obtained from the Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model. The spatial resolution of the DEM was 20 m at 95% confidence for vertical data and 30 m at 95% confidence for horizontal data. The precipitation data was derived from the annual dataset of China's terrestrial climatological data from the China Meteorological Data Service Center. The dataset covers 756 weather stations in China. The precipitation thresholds in China were obtained based on a Kriging interpolation in ArcGIS software, using the average annual precipitation from 2000 to 2015.

The NDVI data was obtained from a long-term Moderate Resolution Imaging Spectroradiometer (MODIS) vegetation index dataset. The data set was provided by the International Scientific & Technical Data Mirror Site, Computer Network Information Center, Chinese Academy of Sciences. (http://www.gscloud.cn). The data time was from February 2000 to December 2015, with a spatial resolution of 500 m and a