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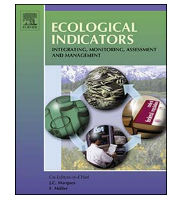

Original paper

Method for evaluating ecological vulnerability under climate change based on remote sensing: A case study

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ABSTRACT

Ecological vulnerability assessment is essential to environmental and resource management, especially given recent global warming concerns. However, evaluation of ecological vulnerability over large areas is difficult and complex because it is affected by many variables, including natural factors and human activities. Here, we propose a novel method to evaluate the vulnerability of an eco-environment with a typical ecologically fragile region, the northern and southern foothills of the Yinshan Mountains of Inner Mongolia, China (NSFYM), as a case study. The proposed method is based on the definition of the IPCC framework and remote sensing. The results showed that the ecological vulnerability in the NSFYM was moderate or high and had distinct regional variations in spatial distribution. Overall, 29% of the seriously and highly vulnerable areas appeared mainly in the highlands, where the natural conditions are poor and human activities have been developing rapidly. Additionally, 31% of the medium vulnerable levels occurred in the low lands, probably in response to agricultural practices. The areas that were found to have high ecological vulnerability exhibited high degrees of exposure and sensitivity and weak adaptive capacity and vice versa, consistent with the current understanding of the characteristics of ecological vulnerability. The integrated method proposed here will be useful for protection of eco-environments under climate change and proper planning for land use in the future.

1. Introduction

The self-adjustment capability of ecosystems has been progressively declining because of global climate change, rapidly increasing population, and the irrational use of natural resources. Ecological vulnerability is a natural attribute of ecosystems that can be used as an indicator for self-adjustment capability. Currently, this vulnerability is a topic of growing concern and has become an issue of considerable interest in the field of global environmental change and sustainable development (Linder et al., 2010; Xu et al., 2015). An ecosystem always maintains a stable state when it can bear the external pressures from nature and humans, otherwise it would become vulnerable and begin to degrade. Ecological vulnerability is a critical indicator for measuring the quality of the ecological environment that has become an important systematic tool in the research field of climate change. The third assessment report (AR3) (2001) of the Intergovernmental Panel on Climate Change (IPCC) first presented the concepts of the impact, adaptation and vulnerability of climate change, proposing that it is important to consider ecological vulnerability in the context of climate change. The fourth (AR4) (2007) and fifth assessment reports (AR5) (2014) further emphasized those concepts. Subsequently, the assessment of ecological vulnerability has become an important research topic in the field of global climate change.

Although ecological vulnerability has recently attracted a great deal of attention, there are few widely accepted definitions of it under climate change. In AR3, vulnerability is defined as "the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes, which is a function of the character, magnitude and rate of climate change and variation to which a system is exposed to, its sensitivity, and its adaptive capacity" (IPCC, 2001). Based on this definition, ecological vulnerability has received increasing attention from many researchers in a variety of research fields (Simenlton et al., 2009; Zheng et al., 2012). These studies have revealed that an ecological system 1) is inherently unstable, 2) sensitive to interference and environmental change, and 3) has difficulty returning to its original state (Pei et al., 2015). Currently, ecological vulnerability is broadly identified as the natural attributes of an ecosystem that have sensitivity and adaptive capacity to resist natural and man-made disturbances at spatiotemporal scales and experience difficultly returning to the natural, original and sustainable state (Brown et al., 2016; Xu et al.,

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2015).

Three approaches, the comprehensive index method, the quantitative evaluation model method, and the scenario analysis method, have been advanced in different systems and at different spatial and temporal scales to assess the vulnerability in the context of climate change (Thang et al., 2016). Among these approaches, the comprehensive index method has been used by most researchers (Nguyen et al., 2016; Wilhelmi and Wilhite, 2002; Abbas and Fahim, 2014; Nazari et al., 2015) and is the main evaluation method. However, the comprehensive index method is susceptible to indicator selection and weight determination from subjective factors. Quantitative evaluation models have also been developed, such as the improved Lund-Potsdam-Jena (LPJ) dynamic vegetation model (Zhao and Wu, 2013), the Carbon Exchange between Vegetation, Soil, and Atmosphere (CEVSA) model (Yu, 2014), and the Pressure-State-Response (PSR) model (Wang et al., 2015), focusing on changes in ecological vulnerability from natural, socio-economic, and environmental aspects. Although quantitative evaluation models can reduce the influence of subjective judgements, their application is still limited because of their complexity. The scenario analysis method, which is a relatively new method for assessing vulnerability to climate change, has significant advantages that include its ability to predict the degree of future ecological vulnerability and changes in vulnerability under diverse scenarios (Abbas and Fahim, 2014; Woznicki et al., 2016). However, its main disadvantage is that it requires large quantities of historical data. Recently, remote sensing has increasingly been applied to evaluate ecological vulnerability and characterize the distribution of vulnerable areas. When compared to the aforementioned areas, remote sensing is arguably one of the most important technologies available for collecting biological parameters across broad geographic extents. Image access has surged over the last several decades, spatial, spectral, and temporal resolution of observations have increased, and data archives cover increasingly longer time periods, which altogether have enabled more detailed assessments of ecological environments than ever before. The strong advantages of remote sensing include systematic acquisition setup, the spatially explicit nature of measurements, and their consistency across political borders (Kuemmerle et al., 2013). For example, Bai et al. (2009) used remote sensing technology to develop an index system of ecological vulnerability in Qinghai Lake by selecting eight indicators that included NDVI, soil moisture, soil brightness, elevation, slope, temperature, precipitation and land use. Yang (2011) constructed an index system of ecological vulnerability in the Huangshan district of Anhui province based on data from SPOT_VGT NDVI and Landsat TM. However, the application of remote sensing for ecological vulnerability assessment is still in the exploratory stage, and needs to be improved.

The above analyses show that, although many studies have conducted vulnerability assessment, few have been based on the IPCC framework. Dong et al. (2015) proposed a quantitative assessment method for agricultural vulnerability under climate change according to IPCC framework, but it is based on the analysis of historical data. Accordingly, it would be worth exploring methods for assessing vulnerability under climate change based on remote sensing technology. This study aims to propose a feasible method for evaluating ecological vulnerability based on remote sensing under climate change. The results presented herein enrich vulnerability theory, and will facilitate construction of indicative, operational and scientific models, as well as standardization of ecological vulnerability evaluations.

2. Study area

The northern and southern foothills of the Yinshan Mountains (NSFYM) belong to one of the most sensitive areas to climate change in the world and play a vital role in the ecological security of Northern China; therefore, this region has received intense attention in studies of the responses of terrestrial ecosystems to climate change (Hou, 2013; Wei, 2011; Meng et al., 2010). The NSFYM, which is situated in the middle of the Inner Mongolia Autonomous Region, China, has a typical moderate temperate semiarid climate, complex physical geographical features and vulnerable eco-environments. Abundant sunlight, low temperatures, frequent drought, short winters, long summers, and stronger winds in winter and spring occur in this region (Pang, 2011). The mean annual rainfall is approximately 200–400 mm, and this gradually increases from west to east. Additionally, 70% of the rainfall occurs from the warmer July to September period. The annual evaporation is around 8–10 times higher than the average rainfall, and the free-frost period is normally 100–120 days (Wu et al., 2008). Potatoes, corn and spring wheat are the main crops grown in the area, which has a short growing period.

The NSFYM comprises 18 counties and/or districts: Huade, Shangdu, Chahar Right Back Banner, Chahar Right Middle Banner, Chahar Right Front Banner, Jining, Xinghe, Zhuozi, Fengzhen, Liangcheng, Hohhot, Wuchuan, Guyang, Tumd Left Banner, Tumd Right Banner, Tuoketuo, Helinger, and Qingshuihe (Fig. 1).

Studies have shown that the average temperature has increased in this region by 0.3 °C over the last 40 years, while the annual rainfall has trended downwards (Chen et al., 2007; Yan et al., 2008). The warming and drying climatic change trend has become increasingly severe and gradually led to grassland degradation, soil erosion, and land desertification. Therefore, it is essential to assess the ecological vulnerability that is occurring under climatic change in this region.

3. Data and methods

3.1. Data

3.1.1. Data sources

The meteorological data were collected from the China Meteorological Science Data Sharing Service Network (http://cdc.cma.gov.cn/), and include monthly precipitation data for the 18 counties in the NSFYM during 1992–2012. Because the relative soil humidity data are incomplete, this study selected ten-day data from the meteorological stations of Wuchuan County, Guyang County, Chahar Right Back Banner, Xinghe County, Chahar Right Front Banner, Tumd Left Banner, Tumd Right Banner, Hohhot Urban District and Qingshuihe County.

The remote sensing data were MOD09Q1, which are eight-day surface reflectance data at a spatial resolution of 250 m, and the original image projection method was SIN projection. The data were selected from the 105th day to the 305th day and downloaded from the USGS Data Center (https://www.usgs.gov/). Each MOD09Q1 image element contained L2G data for an 8-day period, with the exception of instances of high coverage, low clouds, cloud shadows or the influence of aerosol concentrations.

3.1.2. Data manipulation

The surface reflectance data are level three (L3) MODIS products, which had already been mapped to the specified projection coordinates using radiometric and geometric corrections. Therefore, this study dealt with the mosaic, projection and format conversion of the remote sensing images using MRT software supported by NASA and ENVI. The sinusoidal projection coordinates were converted to Albers Conical Equal Area projection coordinates using the nearest neighbour re-sampling method, which maintains the brightness values of original MODIS images and has fast computational speeds for re-projection and re-sampling. In addition, the Interactive Data Language (IDL) software language program was used to perform image-clipping and band operations, as well as to calculate NDVI.

3.2. Methods

3.2.1. Ecological vulnerability evaluation

Ecological vulnerability is an intrinsic characteristic of ecosystems that represents the state of an ecosystem under disturbance or stress. Based on the definition of vulnerability by the IPCC framework, the arid-ecological vulnerability is suggested as the degree of damage to an ecosystem under varying degrees of drought. This index primarily consists of ecological exposure degree, ecological sensitivity and