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The dynamics of sand-stabilization services in Inner Mongolia, China from 1981 to 2010 and its relationship with climate change and human activities

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ABSTRACT

Sand-stabilization, the most important ecological service provided by desert and desertified lands, can alleviate severe wind erosion of soil and is induced by both climate change and human activities. However, with a lack of related data, few studies have focused on the spatial differences in driving factors of sand-stabilization services at a large scale. The present study, based on climatic and socioeconomic data, employed Inner Mongolia as a study area and assessed different climatic and human factors affecting changes of the sand-stabilization services from 1981 to 2010. The results showed that the sand-stabilization service of Inner Mongolia has changed significantly over the past 30 years over an area of 563,584 km^2, and the spatial distribution of the regions affected exhibited considerable heterogeneity. With respect to regions experiencing a significant increase of sand-stabilization service, climate change, human activities, and the coupled effect of the two accounted for 68.49%, 61.25%, and 60.72%, respectively, of the total area experiencing a significant increase in area. Temperature and afforestation projects were the most important drivers of change in these areas. With respect to regions with a significant decrease of sand-stabilization service, climate change, human activities, and the coupled effect of the two accounted for 51.87%, 68.35%, and 42.64%, respectively, of the total area experiencing a significant decrease in area, which was mainly attributed to the increase of livestock stocking rates and crop area.

1. Introduction

Natural ecosystems provide numerous services and goods that support the health and survival of humans, including provisioning, regulating, cultural, and support services (Costanza et al., 1997; Daily, 1997; MA, 2005; TEEB, 2010). As one of the most important ecosystems on earth, deserts and desertified lands occupy 3.37×10^7 km^2 (UNEP, 2006), and provide some critical services including sand-stabilization, soil conservation, maintenance of biodiversity, regulation of water resources, landscape-scale recreation, and so on (Richardson, 2005; Kroeger and Manalo, 2007). The ecological services provided by desert and desertified lands not only support about 500 million people in earth's arid and semi-arid regions, but also have a great impact on the sustainability of global socioeconomic development (UNEP, 2006).

Sand-stabilization is one of the most important ecological services provided by desert and desertified lands, which occurs through a lessening of wind speed, stabilization of soil, and reducing wind erosion (Becker et al., 2015). Sand-stabilization service also has close relationship with sandstorms, and when less sand-stabilization service is provided by desert and desertified lands a higher risk of sandstorms will be created, which might jeopardize human safety and cause losses for agricultural-industrial activities (Chan et al., 2006; Steltzer et al., 2009; Borrelli et al., 2014; Cao et al., 2016). The great value of this sand-stabilization service has caused an ever-increasing number of countries pool efforts to restore vegetation in arid and semi-arid regions with the goal of improving the welfare of local residents. For example, a previous study has shown that the economic value of sand-stabilization increased by $\$5.27 \times 10^6$ in Yuyang, China during the period of 1988–2003 under the large tree-planting program (Mo et al., 2006).

Gaining a better understanding and quantitative measuring the dynamics of sand-stabilization services and their relationship to climate change and human activities in a way that supports integrated policy-making will be a core part of the long-term solutions needed to control desertification (Feng et al., 2015; Galati et al., 2016; Schirpke et al., 2017; Taylor et al., 2017). In recent decades, numerous studies have been conducted to assess the sand-stabilization services provided by desert and desertified lands based on the estimation of wind erosion, and have analyzed the forces driving sand-stabilization at different

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scales (de Oro et al., 2016; Iturri et al., 2016). In these studies, the Revised Wind Erosion Equation (RWEQ) model of United States Department of Agriculture (USDA) has been used to estimate the amount of soil transported by wind (Fryrear et al., 1998; Van Pelt et al., 2004; Fryrear et al., 2000; Jiang et al., 2016b; Fu et al., 2017). For instance, Gong et al. (2014a) applied a RWEQ model to reveal the effects of grassland change on sand-stabilization services since the 1990s in Xilingol League, Inner Mongolia, China. Shen et al. (2016) quantitatively analyzed the temporal and spatial patterns of sand-stabilization services and their driving forces between 2000 and 2010 while using an RWEQ model in Hunshandake, China.

In fact, the mechanism used to create a sand-stabilization service is relatively complicated, because it is affected by climate, soil, vegetation, and other factors. With respect to climatic factors, higher temperatures or lower precipitation can result in drier soils and limit crop production, and eventually exacerbate wind erosion (McFarlane et al., 2012; Sharratt et al., 2015; Kerns et al., 2017; Marzen et al., 2017). As an exogenous force, wind also has a significant influence on wind erosion (Kidron et al., 2017; Schmidt et al., 2017). In addition, the presence of vegetation can increase the surface roughness of an area and minimize the effects of erosion caused by air flow on the ground surface, so vegetation can provide the benefit reducing the amount of wind erosion (Wolfe and Nickling, 1993; Cerdan et al., 2010; Liu et al., 2014). Also, scholars have gained a more consistent understanding of how increasing vegetation coverage can provide an effective measure to improve the sand-stabilization service (Pierre et al., 2015; Keesstra et al., 2018). However, human activities can change the land use and vegetation coverage of the underlying surface, and thus have an effect on soil erosion and sand-stabilization services (Serpa et al., 2015; Jiang et al., 2016c). Research has shown that land reclamation, firewood cutting, excessive use of water resources, and other unsustainable economic activities have seriously damaged the vegetation in some areas, creating the main cause of an anthropogenic acceleration of wind erosion (He et al., 2005; Foley et al., 2005; Nelson et al., 2009; Hostert et al., 2011). Some studies had tried to investigate the mechanism involved in the formation of wind erosion by considering both natural and human factors (Arnaud et al., 2016; Latocha et al., 2016); however, it was still difficult to assess the contribution of each factor owing to the complexity of the interaction of different factors. Meanwhile, most related research has focused on the meso-small scale, and little attention has been paid to the spatial differences of driving factors at a large scale due to the lack of related data. In particular, the influence of human activities on wind erosion has not been deeply analyzed, which makes it very difficult to successfully explain the mechanism involved in the formation of sand-stabilization services.

Inner Mongolia is a representative wind erosion zone in northern China. The maintenance and promotion of sand-stabilization services in this region are playing a critical role in guaranteeing the ecological security of North China. Although a great deal of ecological engineering and restoration has been carried out in recent years, extensive human activities such as mining and rapid urbanization have had a great impact on the underlying surface (Vu et al., 2014). These factors coupled with climate change have generated significant changes in the sand-stabilization services of Inner Mongolia. The goals of this research are (1) to identify the dynamics of sand-stabilization services in Inner Mongolia from 1981 to 2010, and (2) to analyze the driving mechanism of climate change and human activities in sand-stabilization service at county scale. The related results are hoped to provide support for policy-makers and land managers involved in ecological compensation and desertification control in arid areas.

2. Materials and methods

2.1. Study area

Inner Mongolia Autonomous Region lies between 37°24′N–53°23′N and 97°12′E–126°04′E in Northern China, and includes a total of 88 counties or banners (hereinafter referred to as counties; Fig. 1 and Table 1). The study area covered approximately 1.18 × 10^6 km^2, or 12.3% of the country's total area. The temperate zone continental monsoon climate has an average temperature of 0–8 °C and an annual total precipitation or 50–450 mm that progressively decreased from east to west. The region receives an average annual of 2850 h of sunshine and stands at an average elevation of 1000 m. The soils are mostly brown desert, chestnut, and sandy soils. Gales occur on 10–40 days annually, mainly in spring, and 5–20 days with sandstorms. Influenced by climatic factors (such as sandstorms, temperature, precipitation, etc.) and unsustainable human activities (such as grassland reclamation, abandonment of cultivated land, etc.), wind erosion and land degradation are serious problems in this region.

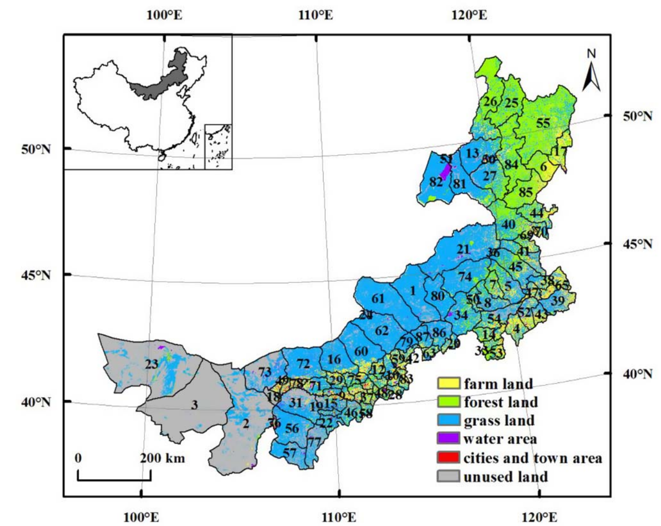

Fig. 1. The location of study area. (The banners and counties represented by each number are listed in Table 1).

2.2. Data collection and processing

The meteorological (including temperature, precipitation, sunshine duration, average wind speed, etc.), snow cover, and soil data used in this study were derived from the Cold and Arid Regions Sciences Data Center. Specifically, meteorological data were acquired from the China Meteorological Forcing Dataset having a time resolution of 3 h, a spatial resolution of 0.1 degrees, and a time range of 1979–2010. The snow cover data were obtained from the Long-term Snow Depth Dataset of China having a time resolution of 1 day, a spatial resolution of 0.25 degrees, and a time range of 1979–2010. Soil particle and organic matter contents were derived from the China Soil Characteristics Dataset having a spatial resolution of 1 km. The Normalized Difference Vegetation Index (NDVI) used in this study was the Global Inventory Modeling and Mapping Studies NDVI3g dataset, with these data obtained from National Aeronautics and Space Administration. The time resolution of this dataset was half of a month with a spatial resolution of 8 km and the time range of 1981–2010. This dataset has been preprocessed by geometric correction and graphic enhancement to ensure data quality. The social-economic data which included urbanization rate, crop area, livestock, and afforestation data at county level were derived from Inner Mongolia's and China's annual forestry statistical yearbooks. In order to facilitate spatial analysis and comparison, all data used in this study were resampled to a grid data with an 8 km resolution. In addition, considering the effects of driving factors was relatively uniform and stable in any one county, the influence of climate change and human activities was analyzed by using the mean values at the county level.