Science of the Total Environment xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Science of the Total Environment

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

Impacts of changes in climate and landscape pattern on ecosystem services

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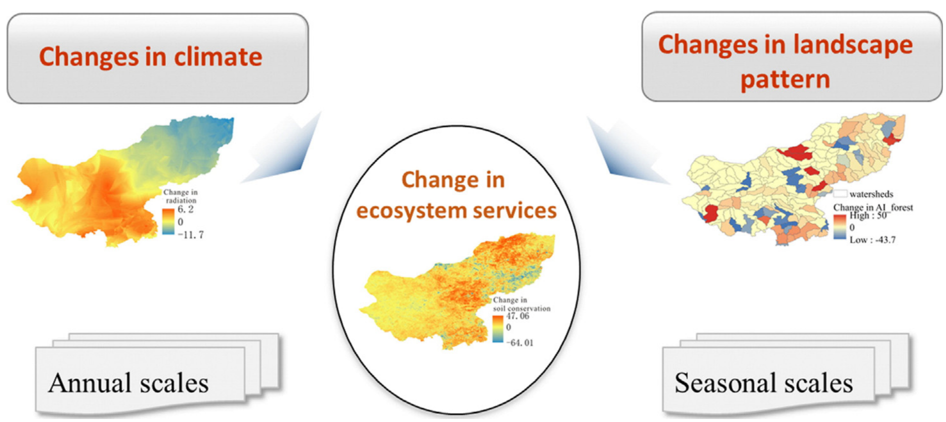
HIGHLIGHTS

- Detecting drivers of ecosystem services is important to evaluate the effects of ecological restoration.
- The changes of multiple ecosystem services indicated the effectiveness of grassland restoration in the study area.
- Changes in both climate and landscape pattern significantly contribute to changes in ecosystem services.
- Climatic factors impacted ecosystem services at annual and seasonal scales.
- The effect of landscape patterns on ecosystem services varied with contexts and time scales.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 13 June 2016
Received in revised form 31 October 2016
Accepted 6 November 2016
Available online xxxx

Editor: Simon Pollard

Keywords:
Grassland restoration
Land use/cover change
Dynamics
Temporal scale
Landscape index
Trend analysis

ABSTRACT

The restoration of degraded vegetation can effectively improve ecosystem services, increase human well-being, and promote regional sustainable development. Understanding the changing trends in ecosystem services and their drivers is an important step in informing decision makers for the development of reasonable landscape management measures. From 2001 to 2014, we analyzed the changing trends in five critical ecosystem services in the Xilingol Grassland, which is typical of grasslands in North China, including net primary productivity (NPP), soil conservation (SC), soil loss due to wind (SL), water yield (WY) and water retention (WR). Additionally, we quantified how climatic factors and landscape patterns affect the five ecosystem services on both annual and seasonal time scales. Overall, the results indicated that vegetation restoration can effectively improve the five grassland ecosystem services, and precipitation (PPT) is the most critical climatic factor. The impact of changes in the normalized difference vegetation index (NDVI) was most readily detectable on the annual time scale, whereas the impact of changes in landscape pattern was most readily detectable on the seasonal time scale. A win-win situation in terms of grassland ecosystem services (e.g., vegetation productivity, SC, WR and reduced SL) can be achieved by increasing grassland aggregation, partitioning the largest grasslands, dividing larger areas of farmland into smaller patches, and increasing the area of appropriate forest stands. Our work may aid policymakers in developing regional landscape management schemes.

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http://dx.doi.org/10.1016/j.scitotenv.2016.11.036
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1. Introduction

Ecosystem services, the benefits that humans obtain from natural ecosystems, are an important bridge between natural ecosystems and human well-being (MA, 2001; MA, 2005; Wu, 2013). Grasslands are the most extensively distributed terrestrial ecosystem, covering 52,544,000 km^2 and representing 40.5% of the total global land area. Grasslands are inhabited by a human population of approximately 800 million (White et al., 2000). Grasslands provide numerous ecosystem services, such as livestock products, plant resources to support human life and recreation and entertainment. Moreover, the high carbon sequestration capacity of grasslands plays a critical role in climate regulation (Havstad et al., 2007; JianJun et al., 2003).

Climatic factors have been shown to significantly influence grasslands (Sala et al., 1997), but changes in the pattern of the landscape can also affect ecosystem structure and function by altering surface biophysical parameters, thereby influencing the provision of ecosystem services (Abdalla et al., 2013; Kindu et al., 2016; Taelman et al., 2016; Wu et al., 2013; Cao et al., 2015). On a regional scale, changes in landscape composition directly affect the spatial distribution of ecosystem services, while changes in landscape configuration indirectly impact ecosystem services by altering ecological processes (Fagerholm et al., 2012; Jia et al., 2014). Studies of grassland ecosystem services involving long time series have mainly addressed changes in grassland vegetation and the associated trends in soil loss due to wind (SL) and carbon sequestration (Gong et al., 2014; Li et al., 2016; Piao et al., 2006; Raynolds et al., 2008; Wang et al., 2013; Zhang et al., 2015), and the methods used have mainly included correlation, regression, and residual analysis. In regression analysis, the dependent variables are long time series data of parameters related to ecosystem services or their degree of change over time, and the independent variables often include climatic, human and topographical factors (Raynolds et al., 2008; Wang et al., 2013; Xin et al., 2015; Zhang et al., 2015). There are also studies that combine spatial overlay and correlation analysis to assess the spatial heterogeneity of the forces driving grassland restoration (Tian et al., 2015), and scenario hypotheses are often used to study the impact of land use/cover changes on ecosystem services (Goldstein et al., 2012). Research into the impacts of climate and landscape pattern changes on grassland ecosystem services is useful for guiding human activities, improving human well-being and promoting sustainable development (Buergi et al., 2015; MA, 2005; Wu, 2013; Zagonari, 2016).

As grasslands face increasing pressure, restoration has been one of the core tasks for governments promoting regional sustainable development. However, the drivers of grassland degradation must first be detected and addressed, and if the restoration measures are effective, the outcomes should be continuously monitored.

The grasslands in China are mainly distributed in the northern arid and semiarid regions and constitute a significant portion of the world's grassland ecosystems, where the tension between environmental conservation and land development is very intense (Chen, 2000; Zhang et al., 2016). The grasslands in northern China are fragile and extremely sensitive to climate change but play a critical ecological role of providing shelter and controlling the wind-blown sand, which is one of the great threats to the metropolitan areas of Beijing (Gao et al., 2000). Since the 1980s, these grassland ecosystems have been notably degraded due to increasing human demand for resources, intensive farming, and overgrazing (Wang et al., 1999; Wu et al., 2015). To restore these fragile ecosystems, the Chinese government launched one of the most important ecological conservation projects in the world in 1999, the Grain for Green Project. This project advocates the cessation of farming on cultivated land that is experiencing serious soil erosion and desertification and encourages the planting of trees and grass in accordance with local conditions. Since the implementation of the Grain for Green Project, the landscape pattern of the grasslands in North China has changed greatly, but few studies have examined whether the restoration measures have been effective under climate change or the relationship between the changes in landscape pattern and the provision of ecosystem services. To examine these two issues, this paper attempts to (1) analyze the changing trends in ecosystem services in the Xilingol Grassland, which is typical of grasslands in North China, from 2001 to 2014 on annual and seasonal time scales; (2) quantify changes in the climate and the landscape pattern in the Xilingol Grassland over the past 14 years; and (3) compare the impacts of climate and landscape pattern changes on ecosystem services and discuss the implications for grassland restoration.

2. Materials and methods

2.1. Study area

Xilingol is in the center (42°32′–46°41′N and 111°59′–120°E) of the Inner Mongolia Autonomous Region in North China and covers a total area of 200,000 km^2 (Fig. 1). This grassland is located within the temperate-arid and semiarid zone, which is characterized by a continental monsoon climate with strong wind, drought, and cold temperatures (TEMPs). The average annual TEMP ranges from 0 to 3 °C, with January being the coldest month (−20 °C) and July the hottest month (21 °C). The average annual precipitation (PPT), which decreases from the southeast to the northwest, is 295 mm, and much of the PPT occurs in July, August and September. Evaporation decreases from east to west. The seasons have the following climatic characteristics: the spring is windy and dusty, less rainy and drought-prone with slow warming occurring throughout; the summer is cool and exhibits the most concentrated PPT during the year, although it is highly variable; the autumn is stable with cooler and sunny weather and little wind; and the winter is cold and dry. The Xilingol Grassland, which is the main natural pasture within the grasslands of Inner Mongolia, acts as an important ecological barrier to protect North China from sandstorms. The northeast, east, and south of the Xilingol Grassland mainly consist of meadow grasslands with high-quality pasture land, while the center is a typical steppe, which characterizes most of the region. Desert steppe with xerophyte vegetation is found in the west (Fig. 2e). Sand vegetation, which refers to a variety of grassland plant communities that grow in sandy soils, is mainly distributed in the west and south-central portion of Xilingol. The Hunshandake Sandy Land is one of the four major sandy lands in China, and it lies in the south of Xilingol and traverses the central area from northwest to southeast. The terrain is high in the south and low in the north. The south and east are hilly, whereas the west and north are relatively flat. The soil types are mainly loam, sand, and sandy loam (Fig. 2d). Xilingol is inhabited by Chinese ethnic minorities, of which the Mongolian population accounts for 31% of the total (Inner Mongolia Statistical Yearbook, 2014). Xilingol is an important production base of livestock husbandry in China, and the quantity of livestock in this area, including cattle, horses, and sheep, takes the first place at the regional level in China. Agriculture in Xilingol is rainfed based, with high-quality wheat, oats, and flax being produced. The Xilingol Grassland is characterized by serious degradation and desertification with the proportion of desertified grassland within the available pasture area expanded from 48.6% in 1984 to 64% in 1996 (Deng, 2009). In 2005, to improve the ecological environment of the Xilingol Grassland and control desertification, the government of China invested 280 million Yuan in a sand control project. Since the implementation of this sand control project and the Grain for Green Project in 1999, desertification has been suppressed, and the grassland area increased from 176,200 km^2 to 177,100 km^2 by 2009 (Hu, 2013).

2.2. Assessment of grassland ecosystem services

This study assessed the total annual and seasonal provision of five critical grassland ecosystem services including net primary productivity (NPP), soil conservation (SC), SL, water yield (WY) and water retention (WR) from 2001 to 2014. In terms of the four seasons, March–May was