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The impacts of land conversion and management measures on the grassland net primary productivity over the Loess Plateau, Northern China

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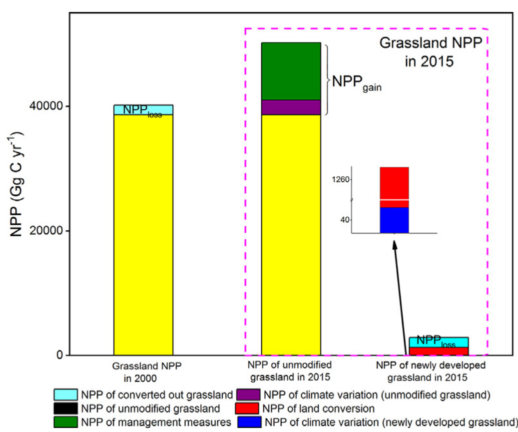
HIGHLIGHTS

- Human and climate factors contributed differently to grassland NPP increase.
- Roles of climate variation, land conversion and management measures were quantified.
- Land conversion added negative effects in grassland NPP increase.
- Management measures were the primary reason for grassland NPP increase.
- Climate variation showed positive impact in grassland NPP increase.

GRAPHICAL ABSTRACT



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ABSTRACT

In the 1990s, the Chinese government began implementation of a series of national-scale restoration programs to combat environmental degradation. As one of most important arid and semiarid regions of China, the Loess Plateau has attracted attention related to the effectiveness of these initiatives. The present study analyzed land use and cover change (LUCC) of the grassland in the Loess Plateau and the consequent change in net primary productivity (NPP) based on a consecutive land use data derived from the European Space Agency Climate Change Initiative land cover maps and the CASA (Carnegie-Ames-Stanford Approach) model driven by MODIS-NDVI data. The contributions of climate variation and human activities (including land conversion and management measures) to these changes were also quantitatively differentiated. The results indicated that the area of the Loess Plateau grassland experienced a net increase of 0.43×10^4 km^2 over the study period. The total NPP of the Loess Plateau grassland increased by 11,325.13 Gg C·yr^{-1}, of which the human activities and climate variation were responsible for 78.45% and 21.55%, respectively. The land conversion reduced the grassland NPP by 308.60 Gg C·yr^{-1}, whereas management measures increased the NPP by 9197.97 Gg C·yr^{-1} in the otherwise unmodified grassland. Overall, ecological restoration programs have effectively increased grassland NPP in the Loess Plateau. However, human activities played both positive and negative impacts in this process.

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1. Introduction

Land degradation is a global issue that has led to the deterioration of the structure, function, and services of ecosystem, while causing serious environmental problems (Gibbs and Salmon, 2015; Bai et al., 2008). It also seriously undermines the livelihood and food security of people, especially in the economically underprivileged regions (Le et al., 2016; Andersson et al., 2011). According to an assessment of the United Nations Food and Agriculture Organization, 61.40 million km^2 of land globally has suffered from degradation, and 26% is severely or very severely degraded (Gibbs and Salmon, 2015). Changes in land use are among the most important causes of land degradation; while land use and cover change (LUCC) has substantially altered the land surface (Pielke, 2005; Foley et al., 2005). Land degradation mostly occurs in arid and semiarid regions, where the vegetation is relatively vulnerable to anthropogenic and climatic disturbances (Yang, 2010). As one of the world's largest vegetation types, grassland ecosystems are mainly distributed in the arid and semiarid regions that contribute significantly to food security by providing meat, milk, and crops for human consumption (White et al., 2000; O'Mara, 2012). Therefore, grasslands have been deeply affected by both climate change and human activities.

China has 3.93 million km^2 of grassland, covering nearly 40% of the total land area. The spatial extent of China's grassland has changed substantially over the last half century as a result of the population growth and socio-economic development (Mu et al., 2013). The Loess Plateau, located in the arid and semiarid regions of northern China, serves as an important ecological barrier in China. A shortage of water resources causes the ecosystems in this region to be fragile and sensitive to climate change (Xie et al., 2016; Sun et al., 2015). In recent decades, the Loess Plateau has attracted considerable attention because of large-scale land degradation; specifically, overgrazing and land conversion are recognized as the primary driving forces of grassland degradation (Zhao et al., 2013; Fu and Chen, 2000).

To combat and mitigate the land degradation, the Chinese government has launched a series of national-scale ecological policies and programs during the late 1990s and early 2000s. The Grain for Green Project (GGP), defined as replacing croplands and grazing lands with trees and grass, is the most famous because of its massive scale, huge cost, and potentially enormous impacts (Wang et al., 2007). In 2003, another large ecological restoration program, the Grazing Withdrawal Program (GWP), was initiated to complement the effects of the GGP. The GWP particularly emphasizes on alleviating grazing pressure and restoring the degraded grassland through grazing exclusion, employing cultivated pastures, or other measurements in the western China (Zhang et al., 2016; Mu et al., 2013). Numerous research studies have been conducted to evaluate the ecological effects of these restoration programs since their implementation. The currently available studies have demonstrated that conditions related to the plant community, soil properties, and carbon sequestration have greatly improved (Zhou et al., 2011; Cheng et al., 2011; Zhao et al., 2013). The recovery of degraded vegetation also effectively reduced surface runoff (Zhang et al., 2007). Most of these studies focused on the field measurements or local scale observations. Although the monitoring of vegetation restoration using remote sensing has also been widely reported, they generally did not take the large-scale LUCC into account, and so fail to comprehensively reflect the actual situation on restored lands.

Net primary productivity (NPP), defined as the net amount of organic matter fixed by plants through photosynthesis, represents the net carbon flow from the atmosphere to the terrestrial ecosystems (Gang et al., 2015). NPP simulation models, such as climate-based models (e.g. Miami model (Lieth, 1977), Thornthwaite Memorial model (Lieth and Eas, 1972), process-based models (e.g. CENTURY (Parton et al., 1993), TEM (Mcguire et al., 1995), BIOME-BGC (Running and Hunt, 1993) as well as light use efficiency models [e.g. CASA (Potter et al., 1993); GLO-PEM (Prince, 1991)], have been widely reported at multiple levels during the recent decades. The process-based models are superior in local scale NPP estimation for the complicated parameters and processes incorporated. The light use efficiency models provide an alternative way in estimating the broader scale NPP due to the readily accessible parameters derived from satellite-based data. As one of the most important indicators of ecosystem function, NPP reflects the growth status of vegetation and the health of ecosystems. Therefore, NPP is usually used as an indicator of ecosystem function change resulting from land degradation or improved land management (Bai et al., 2008). It has also been widely used to distinguish the relative contributions of climate change and human activities to vegetation dynamics (Erb et al., 2009; Wang et al., 2016; Zhou et al., 2014). However, most of these studies have been based on the assumption that the land use types remained unchanged. In the ecological projects implemented regions, how the LUCC and land management measures have affected the spatial pattern and NPP of grassland, and how much climate variation contributes to these changes are still open questions; these areas of research need to be addressed.

Recognition of the LUCC of grassland and its effects on NPP, as well as the quantitative assessment of the related driving forces are essential for answering these questions. The present study primarily aims to: i) characterize the spatial pattern of LUCC in the Loess Plateau grassland by using a consecutive land cover maps from 2000 to 2015; ii) quantify the change in grassland NPP induced by LUCC during this period; and iii) to distinguish the relative contributions of climate variation and human activities (land conversion and management measures) to grassland NPP. The results of this study will not only provide baseline data for comprehensively assessing the efficiency of ecological restoration programs, but will help the land managers and policy makers to understand the current situation in restored grassland of the Loess Plateau, and develop future ecological policies related to managing grassland production in the western China.

2. Materials and methods

2.1. Study area

The Loess Plateau, located between 33°43′–41°16′ N and 100°54′–114°33′ E, covers an area of approximately 640,000 km^2 in the middle reaches of the Yellow River in the northern China (Fig. 1). An arid and semiarid climate dominates most of this region, with mean annual temperature (MAT) of 4.3–14.3 °C and precipitation (MAP) of 200–750 mm (Li et al., 2010; Guo et al., 2010). Highly erodible loess covers the surface of the Loess Plateau, with an average thickness of about 150 m (Liu, 1964).

The vegetation patterns in this region are characterized by a mosaic of agricultural vegetation, forests, and herbaceous plants. Grasslands, the dominant vegetation type, cover 42.86% of the total area. The grasslands stretch from the north, across the middle, and to the west of the Loess Plateau. Croplands are the second largest land use type, composing up to 35.57% of the total land cover, and are mainly located in the southeast portion of the Loess Plateau at relatively low elevations. Forests, mainly distributed along the Taihang, Lvliang, and Qinling Mountains, cover 18.35% of the total area of the Loess Plateau. Areas of urban, barren/deserts, and water/wetlands land use account for 1.57%, 1.62%, and 0.01% of the total area of the Loess Plateau, respectively. Land use and cover changes over time are mainly caused by human activities. The severe soil erosion currently observed in many areas was caused by long-term reclamation and climate change, factors that have had adverse impacts on the natural vegetation and the local environment. The Loess Plateau has been ranked as the most erodible area in the world (Zhang and Liu, 2005; Sun et al., 2015).

2.2. Data and processing

2.2.1. MODIS NDVI data

Moderate-resolution imaging spectroradiometer (MODIS) normalized difference vegetation index (NDVI) data with a 500-m spatial