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Quantifying changes in multiple ecosystem services during 2000–2012 on the Loess Plateau, China, as a result of climate variability and ecological restoration

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ABSTRACT

The Loess Plateau (LP) is one of the most fragile eco-regions in China, and is characterized by severe soil erosion and water shortage. The fragile environment poses a threat to ecological safety and sustainable development on the LP and neighboring areas. The ecosystem on the LP has undergone great changes in recent decades owing to dramatic climate change, ecological rehabilitation, and tremendous human pressure. This study was focused on quantifying and assessing the multiple ecosystem services from 2000 to 2012, based on actual observation records and widely used biophysical models. These included Universal Soil Loss Equation (USLE), Revised Wind Erosion Equation (RWSQ), Carnegie-Ames-Stanford Approach (CASA), and rainfall storage method. Furthermore, in this study, the roles of climate variability and an ecological restoration program on vegetation activity and ecosystem services were investigated, as well as the synergies between multiple ecosystem services. The slight increase in both precipitation and temperature during 2000–2012, in conjunction with ecological rehabilitation, induced a trend of increasing in vegetation cover and productivity. During 2000–2012, the overall soil retention function was slightly enhanced while the amount of hydrological regulation decreased. The biomass production (vegetation carbon sequestration) and food production increased sharply. The increasing precipitation intensified water erosion by enhancing rainfall erosivity, whereas the reduction in wind speed lessened wind erosion and thereby reduced the frequency and duration of sandstorm events. Vegetation restoration supported by climate variability and resulting from ecological projects also played positive roles in soil retention enhancement. The spatial correlation analyses indicated synergies between multiple regulating ecosystem services. There was also a synergy between food production and carbon sequestration in vegetation. The performance of ecological rehabilitation and changes in ecosystem services on the LP exemplified the need for ecological conservation to take climate variability into account, and to facilitate synergies involving multiple ecosystem services, to maximize human well-being and preserve natural ecosystems.

1. Introduction

Ecosystems generate a wide range of services collectively called ecosystem services, that are important for human well-being (Nelson et al., 2009). Over the past decades, ecosystem services have been a central issue in the research on sustainable development and natural resources management (Dearing et al., 2012; Jiang and Zhang, 2015). Tremendous progress has been made towards understanding ecosystem services and their associated economic profits (National Research Council, 2005; Jiang and Wang,

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2016). Ecosystem services are jointly affected by several factors that include demography, economy, science, and technology; as well as by physical and biological conditions (Millennium Ecosystem Assessment, 2005; Lu et al., 2012; Jiang and Wang 2016a). Over the last half century, 60% of the worldwide ecosystem services were degraded as a result of population increase and economic growth (Millennium Ecosystem Assessment, 2005). In China, rapid urbanization, farmland expansion, deforestation, reclamation, and other human activities have induced environment degradation at a national scale. This had severe ecological consequences, including such as wetland degradation, soil erosion, sandstorms, desertification, wildlife habitat loss, and other ecological problems during the past three decades (State Forestry Administration, 2010).

Land cover change induced by human and natural factors and climatic change has been identified as two of the most important drivers of ecosystem change and their services (Millennium Ecosystem Assessment, 2005; Nelson et al., 2009). However, the consequences of land cover change with respect to ecosystem services and human well-being at local and regional scales, is not yet fully understood (Reyers et al., 2009). Effective management of ecosystem services is essential for developing conservation and land management plans (Kremen, 2005). Furthermore, managing ecosystem services requires knowledge of their dynamic patterns, status, connections, interactions among ecosystem structures, functions, and landforms (Millennium Ecosystem Assessment, 2005). A spatially explicit assessment of ecosystem services is critical for informed land use and management decisions (Balmford et al., 2002; Millennium Ecosystem Assessment, 2005).

In order to improve the environmental degradation in China, particularly in the ecologically important regions, the Chinese government has initiated a series of large scale ecological rehabilitation programs on national and regional scales including the 'Three-North Shelterbelt Program (TNSP)', the 'Beijing-Tianjin Sand Source Control Project (BTSSCP)', and 'Grain for Green Program (GFGP)' (Yin and Yin, 2010; B. Zhang et al., 2012; G. Zhang et al., 2012; Jiang et al., 2016a, 2016b; Zhang et al., 2016). These programs focus on local environmental restoration by planting trees in semi-arid and arid regions, and by protecting natural forests (Zhang et al., 2016). However, the effectiveness of these programs has been questioned in several previous studies. Existing studies reported that implementation of these large scale ecological programs has altered the regional ecosystem pattern and quality (e.g., vegetation activity and productivity). Zhang et al. (2016) reported that the multiple ecological programs contributed to the accelerated trend of greening in the northern China and highlighted the importance of positive human intervention in the growth of regional vegetation under conditions of climate change. Trends of increasing in vegetation activity have been reported in other areas during the recent decades and large-scale afforestation and reforestation are the main driving factors for this increasing trend (Xu et al., 2014; H. Du et al., 2015; J. Du et al., 2015; He et al., 2015; Qu et al., 2015; Sun et al., 2015; Zhao et al., 2015; Zhang et al., 2016). Moreover, growth of vegetation is highly sensitive to precipitation in the arid and semiarid regions, and drought is found to significantly effect changes in the vegetation (H. Du et al., 2015; J. Du et al., 2015; He et al., 2015; Qu et al., 2015). Regarding change in ecosystem services, Lu et al. (2012) assessed such changes over the period of 2000–2008 for four key ecosystem services in the Loess Plateau, China, where an ecological rehabilitation program (GFGP) was launched since 1999. They found that the program resulted in enhanced soil retention and carbon sequestration, but decreased regional water yield under a warming and drying climatic trend. Wang et al. (2015) focused on assessing changes of multiple ecosystem services in the Sanjiang Plain (northeast China) as a result of land cover change over the period of 1992–2012. They found the trade-offs were typically manifested as increased water yield and significantly better food production. This was in contrast with significant losses in ecosystem carbon stocks and suitable waterbird habitats, mainly due to the conversion of land cover from wetland to farmland.

The LP includes the Mu Us desert and surrounding sandy lands, that are the sand sources for the sandstorms originating in northern China. Sandstorms blowing out of the Mu Us Desert and eroded soil transported down the mid-stream of the Yellow River, induce air and water pollution and other negative ecological consequences. These now pose a threat to ecological safety and sustainable development of capital (Beijing City) and neighboring areas (Yue et al., 2014; Sun et al., 2015). In addition, the reasons for choosing LP as a study area also include the following two points. First, the GFGP was completed at the end of 2010, and it is necessary to assess the effectiveness of this program in altering ecosystem pattern, quality, and services; Second, the existing studies reported that there was a significant trend of increase in vegetation activity over the past decade (Sun et al., 2015), whereas the impacts of vegetation restoration on ecosystem services are still unclear. Therefore, the objectives of this study were (1) to quantitatively investigate changes in the land use and vegetation cover from 2000 to 2012, (2) to quantify and assess the changes in multiple regulating services (soil retention, carbon sequestration, and hydrological regulation) and one provisioning service (food production), (3) to investigate the role of climate variability and the ecological restoration program on vegetation activity and ecosystem services, and (4) to investigate the synergies and trade-offs of multiple ecosystem services, and based on the results of this work, to give advice for sustainable development through adaptive management.

2. Research area

The LP covers an area of approximately 6.4×10^5 km^2 (34–41°N, 98–114°E), traversed by the upper-middle reach of China's Yellow River, which encompasses more than eight sub-basins (Fig. 1(a)). Severe water shortage and soil erosion are two major obstacles to sustainable development on the LP (Chen et al., 2007). Because it covers such a large area, when treated as a unified whole it is difficult to gain an understanding of the spatiotemporal variation of ecological and geographical conditions. To accommodate this issue, the study area was divided into six sub-regions (Fig. 1(b)), based on the following criteria: the completeness of the drainage area and the similarity of precipitation, temperature, topography, soil type, vegetation cover and other physical and geographical conditions (Yan and Xu, 2007; B. Zhang et al., 2012; G. Zhang et al., 2012). The LP is located in the central part China (Fig. 1(c)), and traverses seven administrative areas including Qinghai, Gansu, Ningxia, Shaanxi, Shanxi, Inner Mongolia, and Henan provinces (autonomous regions) (Fig. 1(d)). The LP sits from 200 to 4975.7 m above sea level, with elevation rising from southeast to northwest (Fig. 1(e)). Its surface is covered by highly erodible loess layers that, on average, are 100 m thick (Wang et al., 2010). From the hydrogeographic perspective, the LP lies in a transitional zone between several large basins in China, including the Hai River Basin, Yellow River Basin, Yangtze River Basin, Huai River Basin, and Northwest River Basin (Fig. 1(f)). The region is in an arid to semi-arid climate zone and has a mean annual precipitation of approximately 420 mm, with approximately 70% of the rainfall during the summer months. The average annual temperature is 9.0 °C, with a minimum average temperature of −3.1 °C in the northwest, and a maximum average temperature of 15.3 °C in the southeast (for the spatial patterns of precipitation and temperature refer to Fig. 1(g and h)).