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Assessing the soil erosion control service of ecosystems change in the Loess Plateau of China

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ABSTRACT

Soil erosion in terrestrial ecosystems, as an important global environmental problem, significantly impacts on environmental quality and social economy. By protecting soil from wind and water erosion, terrestrial ecosystems supply human beings with soil erosion control service, one of the fundamental ecosystem services that ensure human welfare. The Loess Plateau was one of the regions in the world that suffered from severe soil erosion. In the past decades, restoration projects were implemented to improve soil erosion control in the region. The Grain-to-Green project, converting slope croplands into forest or grasslands, launched in 1999 was the most massive one. It is needed to assess the change of soil erosion control service brought about by the project. This study evaluated the land cover changes from 2000 to 2008 by satellite image interpretation. Universal Soil Loss Equation (USLE) was employed for the soil erosion control assessment for the same period with localized parameters. Soil retention calculated as potential soil erosion (erosion without vegetation cover) minus actual soil erosion was applied as indicator for soil erosion control service. The results indicate that ecosystem soil erosion control service has been improved from 2000 to 2008 as a result of vegetation restoration. Average soil retention rate (the ratio of soil retention to potential soil loss in percentage) was up to 63.3% during 2000–2008. Soil loss rate in 34% of the entire plateau decreased, 48% unchanged and 18% slightly increased. Areas suffering from intense erosion shrank and light erosion areas expanded. Zones with slope gradient of 8°–35° were the main contribution area of soil loss. On average, these zones produced 82% of the total soil loss with 45.5% of the total area in the Loess Plateau. Correspondingly, soil erosion control capacity was significantly improved in these zones. Soil loss rate decreased from 5000 t km^{-2} yr^{-1} to 3600 t km^{-2} yr^{-1}, 6900 t km^{-2} yr^{-1} to 4700 t km^{-2} yr^{-1}, and 8500 t km^{-2} yr^{-1} to 5500 t km^{-2} yr^{-1} in the zones with slope gradient of 8°–15°, 15°–25°, and 25°–35° respectively. However, the mean soil erosion rate in areas with slope gradient over 8° was still larger than 3600 t km^{-2} yr^{-1}, which is far beyond the tolerable erosion rate of 1000 t km^{-2} yr^{-1}. Thus, soil erosion is still one of the top environmental problems that need more ecological restoration efforts.

1. Introduction

Soil erosion is widespread and affects adversely all natural and human-managed ecosystems. Severe erosion can easily be triggered from lack of vegetation protection (Canton et al., 2001; Ludwig et al., 2005). It can cause soil deterioration (Marques et al., 2008), decline in land productivity (Pimentel and Kounang, 1998; Lantican et al., 2003) and degradation of streams, lakes and estuaries with transported sediments and pollutants. It ranks as one of the most serious environmental problems in the world (Pimentel and Kounang, 1998). Fortunately, soil erosion control and sediment retention are key services (Costanza et al., 1997; Millennium Ecosystem Assessment, 2005) supplied by terrestrial ecosystems. In addition, vegetation restoration effectively strengthens soil erosion control (Zhou et al., 2006; Zheng, 2006; Marques et al., 2007; Vásquez-Mendéz et al., 2010; Yapp et al., 2010).

Due to its thick but loose and fine soil, the Loess Plateau, located in Northwest China, is known as one of the key agricultural areas in the country. However, it has also been suffering from the most severe soil and water loss in both China and the world. Anthropic land use/cover change is a key driving force for soil and water loss in this region (Li et al., 2006; Fu et al., 2009). As an important countermeasure, the Grain-to-Green Program, that restores cropland to forest or grassland, was launched in 1999 on the Loess Plateau of China. A large number of steep slope croplands

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have been converted into grasslands and forested lands, and vegetation cover has increased (Xin et al., 2008). Field monitoring and investigations confirmed reduction of soil erosion on hillslopes (Zheng, 2006) and in small catchments (Zhou et al., 2006) of the Loess Plateau after vegetation restoration. Except monitoring programs at a few gauged stations, regional scale assessments of soil erosion change are scarce. There is a need to assess the spatial and temporal changes in the ecosystem service of soil retention caused by land use/cover change following the implementation of the Grain-to-Green Program to provide information for regional ecosystem management and development of relevant soil conservation strategies in the future. This is also necessary to enhance the understanding on the dynamics of the so-called "Social-Economic-Natural Complex (Wang et al., 2011)" at regional scale.

Assessing the change of soil erosion with changing land cover is important to understand the efficiency of restoration and the trend of ecosystem functions in soil erosion control, and ecosystem service evaluation. Though field monitoring provides much information at small scales such as small catchments, hillslopes and plots (Fu et al., 2010), assessments based on models are needed to evaluate soil erosion control in areas like the Loess Plateau that have suffered severe soil erosion at a large scale with a lack of monitoring for policy/decision making. The Universe Soil Loss Equation (USLE) is one of the models that can be used as a quasi-distributed model in soil erosion distribution assessment (Kitahara et al., 2000; Fistikoglu and Harmancioglu, 2002; Lufafa et al., 2003; Irvem et al., 2007).

The objective of this paper is to assess the spatial and temporal changes of soil erosion control service following the implementation of the Grain-to-Green project on the Loess Plateau from 2000 to 2008. The paper first describes the study area and the Grain-to-Green project, and then provides context for using USLE in estimating soil loss and soil retention in the study area. Subsequently, the paper discusses the research methods and results, and assesses the effects of the Grain-to-Green project.

2. Study area and methods

2.1. Study area

The Loess Plateau locates at the middle reaches of the Yellow River, extending to the Qingling Mountain Ranges in the south, Yinshan Mountain in the north, Taihang Mountain in the east, and Wuqiaoling-Riyue Mountain in the west. This region covers 287 counties of seven provinces including Shaanxi, Gansu, Shanxi, Inner Mongolia, Ningxia, Henan, and Qinghai. Geographically, it lies between E100°54′7″–114°33′7″ and N33°43′7″–41°16′7″. As the largest area of loess in the world, it covers an area of more than 600,000 km^2, representing 6.6% of the territory in China. With over 8.5% population of the country residing on the region, the population density reaches 168 person/km^2. This has placed a huge pressure on the fragile local ecosystems and natural resources.

The fragility of the loess ecosystem is characterized by its semi-arid climate, with only 464.1 mm of average annual precipitation. The water resources of the Loess Plateau accounts for only 2% of the total water resources in China, but the water utilization ratio of the major rivers is up to 70%, far exceeding the internationally recognized water utilization threshold of 40% (Gao et al., 2009). The vulnerable natural conditions, along with the long-term and intense development of agriculture, urbanization, energy utilization, and road construction have led to the prominent soil erosion in the region (Cao, 2008). The average erosion modulus was calculated to be 5000–10,000 t/km^2, with the highest one up to 20–30,000 t/km^2, making it one of the most severe soil erosion regions in the world. The severe soil erosion has brought about significant impact on the ecological security of the Yellow River and its lower reaches, which is evidenced by high content of sand, siltation of the river channels and reservoirs, as well as an elevated river bed. Consequently, the ecological degradation of the Loess Plateau and its control has aroused extensive attention in the ecological community. Since 1949, the local government has proposed the double objectives of controlling the floods in the Yellow River and promoting agricultural productivity in the region. Since the 1980s, a series of programs on soil and water loss control and plantation of forest shelters have been carried out (Yang, 2003). Some of the major measures in ecosystem management implemented in the Loess Plateau ranged from optimizing the land use structure and configuration, transforming the slopes into terrace, and restoring the slope cropland into forest and grassland, enclosing the hillside and banning grazing, building reservoirs and basic farmland. In 1999, the Chinese government launched the Grain-to-Green and natural forest conservation programs with the Loess Plateau being listed as one of the key areas. The implementation of these programs has further enhanced the vegetation restoration and ecological conservation, and strengthened the ecosystem management. At the same time, the coupling and feedback between the ecological condition and economic development have attracted greater attention. By promoting the development of high-yield prime farmland, and planting the economic forests and fruit trees, as well as growing fodders and fostering related industries, mutual benefit for both ecological restoration and economic development could be achieved in this region.

2.2. Data sources

Dataset used in this assessment includes DEM with a resolution of 90 m developed from SRTM (Shuttle Radar Topography Mission), the maximum 16-day NDVI (Normalized Differential Vegetation Index) data between 2000 and 2008 derived from MODIS images, monthly rainfall values from 107 weather stations in and around the Loess Plateau from China Meteorological Administration.

We used Landsat TM/ETM (Enhanced Thematic Mapper) data at a spatial resolution of 30 m in 2000 to extract the land cover in the Loess Plateau of China. Prior to image interpretation, the remote sensing data were geo-referenced by using 1: 100,000 relief maps. For each Landsat TM/ETM scene, a minimum of 30 evenly distributed sites were selected as Ground Control Points (GCPs). The Root Mean Squared Error (RMS error) of geometric rectification was less than one pixel (or 30 m). The land cover types were identified on the computer screen, using ArcMap based on the object's spectral reflectance, structure and other information. The boundaries of the objects were subsequently drawn and the attributes (labels) and topology relations of the polygons were added to produce the digital map (Liu et al., 2005). A total number of 27 sub-classes of land cover subtypes for the study area were further grouped into 6 aggregated land cover types: Woodland, Grassland, Farmland, Desert, Residential area, and Water.

Based on the land cover map of 2000, we updated the land cover classification of the Loess Plateau of 2008, by using the China-Brazil Earth Resources Satellite (CBERS-2b). The CBERS images have 20 m ground resolution and almost the same spectral bands as Landsat ETM. All the pre- and post-processes were the same as Landsat TM/ETM processing described above. Meanwhile, for supporting image interpretation and validation of the land cover map of 2008, we conducted a field survey to evaluate the classification accuracy. The field measured land cover types and photos located with GPS coordinates were collected across the whole study area. The classification accuracy was 95%.