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Responses of soil erosion processes to land cover changes in the Loess Plateau of China: A case study on the Beiluo River basin

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ABSTRACT

Understanding the responses of soil erosion processes to land cover changes would benefit catchment ecological management. Landsat thematic mapper images in 1987, 1995, and 2007 were collected to obtain the historical normalized difference vegetation index and land cover data of the Beiluo River basin, one of the catchments in the Loess Plateau. The sediment load data of five subcatchments were collected in the corresponding periods. A set of location-weighted landscape contrast indices was used to analyze the effect of land cover changes on soil erosion processes, as specified by the following indices: slope gradient, flow path length, relative altitude, and relative distance. Results showed that vegetation cover (VC) notably increased from 41.12% to 63.43% in the basin from 1987 to 2007. The increased VC was mainly concentrated in the hilly-gully area from 18.40% in 1987 and 20.21% in 1995 to 41.65% in 2007. The mean annual sediment load modulus in the region over the same periods significantly decreased by 90%. All the indices for each subcatchment exhibited a decreasing trend. The change extent of the indices revealed a significantly positive correlation with that of sediment load modulus. Slope gradient and flow path length were the most important influential factors on soil erosion. Results implied that the improvement in land cover in the Beiluo River basin from 1987 to 2007 led to sediment entrapment in the sink area and changed the soil erosion processes, especially the slope gradient and flow length of the soil erosion source area. This study contributed to improving catchment ecological management and evaluating erosion control practices in the Loess Plateau.

1. Introduction

Land use and cover changes greatly affect many environmental aspects and ecological processes (Turner, 1989), including soil and water losses (Walling, 1999; Fu et al., 1994; Kang et al., 2001; Huang et al., 2003; Zhang et al., 2008; García-Ruiz, 2010). As a core subject, many researchers have attempted to elucidate the interaction between land cover pattern and ecological processes (Fu et al., 2011).

At the patchy scale, patchy density-, shape-, diversity-, and connectivity-related indices are often used to acknowledge the presence of strong ecohydrological linkages between vegetation spatial pattern and runoff and sediment fluxes (Ludwig and Tongway, 1995; Davenport et al., 1998; Cammeraat and Imeson, 1999; Wilcox et al., 2003; Puigdefábregas, 2005; Shi et al., 2013). Vegetation patches involve high water storage capacity and organic carbon and nutrient inputs, thereby resulting in high soil anti-erodibility and excellent hydraulic properties. Positive feedback mechanisms can differentiate vegetation patches from bare ground areas as sources and sinks of water, sediments, and nutrients (Ludwig and Tongway, 1995; Cerda`, 1997; Reid et al., 1999; Puigdefábregas, 2005; Bochet et al., 2006; Johnson and Host, 2010).

Given the knowledge obtained at the patchy scale, the interaction between vegetation patterns and hydrological processes has been investigated at both hill slope and regional scales, and has become the focus of the recent landscape ecology studies in the field (Casermeiro et al., 2004; Bautista et al., 2007; Fridley et al., 2007; Claessens et al., 2009; Bisigato et al., 2009). Directly observing large-scale hydrological processes is difficult. Modeling has become a key research tool in regional pattern-process studies (Fu et al., 2011). Ludwig et al. (2002, 2006, 2007) have developed a directional leakiness index to indicate the landscape function to retain, not "leak", vital system resources such as rain and soil. Bautista et al. (2007) have used the index as an integrated indicator to test the effects of patchy distribution variation on runoff and sediment yields in Southeast Spain. In China, a multi-scale soil erosion concept assessment equation is introduced based on the results of the interactions between soil and water losses and the land use/cover changes at the hillslope, small catchment, and regional scales; natural and human factors, such as rainfall, landform, land use, and soil properties, are considered (Fu et al., 2002, 2006, 2009; Wei et al.,

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2007; Wang et al., 2006; Fang et al., 2012). Considering the orientation of runoff and sediment fluxes from source to sink areas, the hydrological connectivity (such as flow length) among topography-related landscape patterns is defined as a spatial metric (Borselli et al., 2008; Mayor et al., 2008; Gooseff et al., 2011). This metric has been evaluated in plots and catchments in Italy and Southeast Spain, respectively, and the connectivity of runoff sources has been proven as a key factor that controls runoff and erosion in dryland areas (Borselli et al., 2008; Mayor et al., 2008).

Soil and water losses are some of the most serious environmental problems in China, particularly in the Loess Plateau region. The average erosion rate in the plateau ranges from 5000 t/km^2·a to 10,000 t/km^2·a, which even reaches 20,000 t/km^2·a to 30,000 t/km^2·a in some tributaries (Chen et al., 1988). To control severe soil erosion, numerous conservation measures have been implemented in the Loess Plateau catchments since the 1950s. The Grain for Green project is also implemented in 1999 to promote sustainable development in the region (The State Environmental Protection Administration of China, 2002). Therefore, the vegetation cover (VC) in the region has greatly improved (Chen et al., 2013). In plots and small catchments, the results of the interaction between vegetation pattern, and soil and water losses are obtained, but the issue on understanding the ecological processes at a regional scale still remains (Fu et al., 2011). In the present study, the concept of location-weighted landscape contrast index (LCI) developed by Chen et al. (2003, 2006) is considered. This index is established based on topographical characteristics contributed by vegetation pattern to point-based ecological process measurements, such as that in hydrological gauging stations. LCI is conceptually related to distance, slope gradient, connectivity, and efficiency of a vegetation pattern to entrap soil and water across land surfaces. Yang et al. (2007) and Zhao et al. (2010) have used LCI to determine the effects of land use change on soil, nutrition, and phosphorus losses in the Yangtze River basin and in Heilongjiang Province, respectively. LCI is also employed in the present study as an integrated indicator of the topographical features related to flow connectivity and slope gradient. Thus, the suitability of land cover in the study area is also assessed here. Understanding the responses of soil erosion processes to landscape pattern changes would benefit catchment ecological management, especially in the Loess Plateau.

This study aims to explore the responses of soil erosion processes to land cover changes in the Loess Plateau river basin. The major objectives are as follows: (1) to detect the variation trend in VC using historical remote sensing data; (2) to examine the spatial distribution trend of VC pattern and LCI; and (3) to explore the correlations between the indices of slope gradient, flow length, distance, and altitude, and the corresponding sediment load modulus. The most important influential factors on soil erosion processes in the Loess Plateau are also determined in the regional scale.

2. Study area description

Beiluo River basin (107° 33 ′33 ″E–110° 10′ 30″ E, 34° 39 ′55″N–37° 18′ 22 ″N) is the second level tributary of the Yellow River with an area of 2.69 km^2 × 10^4 km^2 (Fig. 1). The main stream length is 680 km, and the altitude ranges from 297 m in the southeast to 1886 m in the northwest. The basin belongs to a semi-arid climate zone. The mean annual precipitation is 514.2 mm, and approximately 76.2% of annual precipitation occurs during the flood season from May to September (Ran et al., 2006). Loess soil (the primitive soil in the international soil classification) is the dominant soil type in the entire basin. Loess is an aeolian sediment formed by the accumulation of wind-blown silt, typically in the 20–50 μm size range, 20% or less clay and the balance equal parts sand and silt that are loosely cemented by calcium carbonate. The other two soil types include gray cinnamon soil (Haplic Luvisols), which is mainly distributed in the middle–upper reaches of the river with xerophilous forests and shrubby steppes, and dark loessial soil (Calcisol), which is mainly found on the residual hill and table land in the middle reaches of the basin (Xu et al., 2008).

The landform in the basin could be divided into the following regions: hilly-gully, rocky mountain, table-gully, and terrace-plain areas (Fig. 1). The upper reaches of the river from headwater to Liujiahe hydrological satiation belong to the hilly-gully area, a heavily dissected landscape with a gully density of 6 km/km^2 to 8 km/km^2. The hilly-gully area, which is one of the most seriously eroded areas in the Loess Plateau, comprises 26.9% of the whole basin and includes three nested hydrological stations: Wuqi, Zhidan, and Liujiahe. The rocky mountain area (41.8% of the whole basin) is characterized by high vegetation coverage and a relatively intact natural secondary forest (Ran et al., 2006). Two independent hydrological stations are involved: Zhangcunyi and Huangling. The table-gully area, which includes high and flat lands, and the gullies around these lands; and the terrain-plain area (Fig. 1) comprise 23.2% and 8.1% of the entire basin, respectively. Considering landform singleness and comparability, this study primarily focuses on the hilly-gully and rocky mountain areas to examine the responses of soil erosion processes to land cover changes.

Given the severe soil erosion in the Loess Plateau, numerous soil and water conservation measures have been implemented since the 1970s; consequently, the Grain for Green project has been executed since 1999. This project is attributed to large-scale VC improvement in the Beiluo River basin. For example, grazing in Wuqi County, which is located in the upper reaches of the Beiluo River basin, has been totally prohibited since 1998. Approximately 84% of farm lands with steep slopes are abandoned. The VC percentage that is greater than 30% has dramatically increased from less than 1% to 92% in 2009. The mean annual sediment load modulus in Wuqi Station has decreased from more than 10,000 t/km^2·a before 1980 to 4400 t/km^2·a after 1999 (Zhang et al., 2012).

3. Materials and methods

3.1. TM images and vegetation cover

To obtain historical land cover information, Landsat TM images (1987, 1995, and 2007) with 30 m spatial resolution were used. The images were mainly obtained during August, September, and October. Digital elevation model (DEM) data with 30 m spatial resolution were used to extract the topographical features, such as slope gradient, altitude, and landscape pattern distance in the basin. DEM data with 5 m resolution were used to offset the error derived from the low spatial resolution of the 30 m DEM data. For example, through the 5 m DEM, the slope gradient could be searched more precisely based on the comparison between the cumulative frequency distribution curves of the slope gradients of the 5 and 30 m DEMs (Yang et al., 2008). Flow length was obtained by defining flow direction using geographical information system technology. Both images and DEM data were downloaded from the International Scientific Data Service Platform (http://www.csdb.cn).

Based on the normal difference vegetation index calculated from the TM images, the dimidiate pixel model was used to obtain the VC in the Beiluo River basin. Given the actual situation and statistical characteristics of the VC in the basin, the land cover was divided into five VC levels: high (≥80%), moderately high (60% to 80%), moderate (40% to 60%), moderately low (20% to 40%), and low (≤20%) (Fig. 3) (Chen et al., 2013).

3.2. Sediment load and precipitation data

The data of five gauging stations were used, where three were from the hilly-gully area and two were from the rocky mountain area. Given the characteristics of wind-deposited loess soil, intensive rainfall, sparse vegetation, and highly dissected landscape, the mean annual sediment