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The influence of changes in land use and landscape patterns on soil erosion in a watershed

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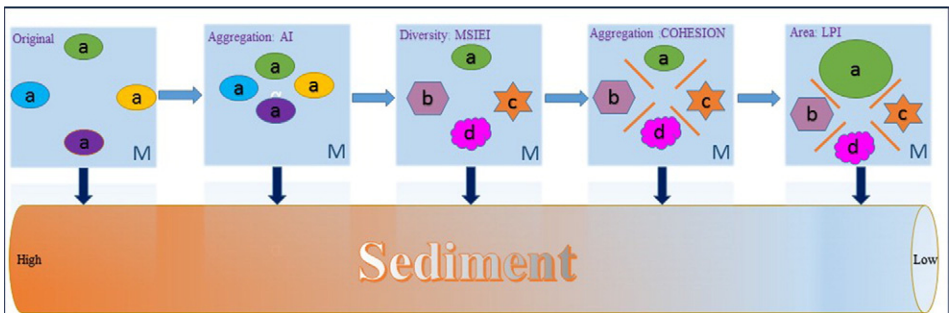
HIGHLIGHTS

- The relation between soil erosion and land use patterns was studied.
- Multiple linear regression method was used to obtain the relation.
- The four main contributing landscape indices were highlighted by regression analysis.
- The large patch index was the most important landscape index affecting soil erosion.
- It is not feasible to obtain the soil erosion amount from landscape metrics alone.

GRAPHICAL ABSTRACT



In this diagram, we selected the letters like a, b, c, d as the types of landscape patches, and capital letter M as the landscape matrix. The evolution of the spatial distribution of various patch types was characterized by the five pictures, which would have an impact on watershed sediment yield from high to low.

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ABSTRACT

It is very important to have a good understanding of the relation between soil erosion and landscape patterns so that soil and water conservation in river basins can be optimized. In this study, this relationship was explored, using the Liusha River Watershed, China, as a case study. A distributed water and sediment model based on the Soil and Water Assessment Tool (SWAT) was developed to simulate soil erosion from different land use types in each sub-basin of the Liusha River Watershed. Observed runoff and sediment data from 1985 to 2005 and land use maps from 1986, 1995, and 2000 were used to calibrate and validate the model. The erosion modulus for each sub-basin was calculated from SWAT model results using the different land use maps and 12 landscape indices were chosen and calculated to describe the land use in each sub-basin for the different years. The variations in instead of the absolute amounts of the erosion modulus and the landscape indices for each sub-basin were used as the dependent and independent variables, respectively, for the regression equations derived from multiple linear regression. The results indicated that the variations in the erosion modulus were closely related to changes in the large patch index, patch cohesion index, modified Simpson's evenness index, and the aggregation index. From the regression equation and the corresponding landscape indices, it was found that watershed erosion can be reduced by decreasing the physical connectivity between patches, improving the evenness of the landscape patch types, enriching landscape types, and enhancing the degree of aggregation between the landscape patches. These findings will be useful for water and soil conservation and for optimizing the management of watershed landscapes.

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1. Introduction

Water and soil loss in catchments leads to a range of problems, such as extensive sediment deposition in river channels and reservoirs, declines in soil fertility, and environmental pollution (Munro et al., 2008). It is, therefore, important to study the various factors that influence soil and water loss to develop and implement effective measures for soil and water conservation at the watershed level. Watershed erosion is related to many factors, including rainfall processes and variation in the watershed surface, such as land use, soil, terrain, and topography (Ni et al., 2008; Ochoa et al., 2016; Saedi et al., 2016). Rainfall, soil types, and topography in a watershed do not change significantly in the short-term, which means that human activities, through changes in land use, are the main influence on changes in watershed erosion.

There are two main ways by which land use can modify watershed erosion. Watershed erosion may be changed by modifying the land use type; for example, cultivated land may be returned to forest and grassland, so that erosion decreases (Zhang et al., 2014). The land use distribution pattern, known as landscape and land use morphology, may also be changed, resulting in changes in erosion. Land use types and landscape morphology both play an important role in soil erosion (Qi et al., 2012; Wang et al., 2009a).

Many studies have examined changes in watershed erosion related to changes in land use types. For example, Hao et al. (2004) used the Soil and Water Assessment Tool (SWAT) in the Yellow River basin and found that forestation decreased the sediment yield, and that increases in the amount of land used for agriculture increased the sediment yield. Ouyang et al. (2010) established the relation between soil erosion and sediment yield with the normalized difference vegetation index and showed that the vegetation status had a significant impact on soil erosion and transport. Ciampalini et al. (2012) studied soil erosion in response to historical changes in agricultural and soil conservation practices in the Aksum area, and found that large areas of arable land were converted into grazing land resulting in significant increases in soil loss. Durán-Zuazoa et al. (2013) explored the impact of land-cover types on soil erosion and runoff, and, by comparing different land use types, demonstrated that erosion and runoff were lower from forest dominated by *Pinus* than from abandoned farmland. There is general agreement on how changes in land use types influence erosion; numerous studies have shown that soil and water losses are generally lower from forest land than from cultivated land, grassland, and pasture (Feng et al., 2010; Nunes et al., 2011; Alatorre et al., 2012).

Various researchers have studied the influence of land use morphology on erosion, and have provided case studies that report analysis of landscape patterns (Xiao and Ji, 2007; Liu and Yu, 2010; Huang et al., 2013; Liu and Lu, 2011; Silva et al., 2015). Wei et al. (2006) studied the relationship between landscape patterns and soil erosion in an agricultural watershed in northern China where Mollisols dominated and found that the multiple correlation coefficients between the nine selected landscape metrics and erosion were higher than the single-factor coefficients between any of the individual landscape indices and erosion. Wang et al. (2009b) used GIS and analysis of landscape indices to explore the relation between soil erosion and landscape patterns in the Wuyuer River and concluded that for soil erosion control and management, it was very important to regulate landscape patterns in cropland, grassland, and forestland. Ouyang et al. (2009) selected landscape metrics at the patch level to study the response of soil erosion dynamics to landscape patterns and indicated that contiguous grassland patches reduced soil erosion yield and that larger areas of water led to more soil erosion. Shi et al. (2013) used partial least-squares regression to link land cover patterns to soil erosion and sediment yield in a watershed and found that landscape characteristics, such as the Shannon diversity index (SHDI), aggregation index (AI), largest patch index (LPI), contagion (CONTAG), and patch cohesion index (COHESION) were the main indices that influenced watershed soil erosion and sediment yield at the landscape level. Landscape indices have been widely applied to examine the response of soil erosion to landscape patterns. However, there is no consistent standard method of selecting landscape metrics, which means that studies arrive at different conclusions, and to date there is no universal conclusion. For example, since soil erosion is affected by multiple factors, such as precipitation, land use, soil, and topography, the question remains as to whether soil erosion can be quantified directly from landscape indices alone.

The objectives of this study were to (1) determine the influence of land use patterns on watershed erosion, (2) derive a relation between watershed erosion and landscape metrics at the landscape level by combining ecologically significant landscape metrics, and (3) establish a robust basis for soil and water conservation in watersheds.

2. Study area

The Liusha River is in the transition zone of the Sichuan Basin and the Western Sichuan Plateau. It is a tributary of the Dadu River, and it runs from north to south through the city of Ya'an, Sichuan Province, China. The Liusha River Watershed covers 1150 km^2 and lies between 102° 16′–102°45′E and 29°19′–29°43′N. Its source is in the Shanzi Mountains, which has an elevation of 3300 m, and an elevation difference of 2545 m between the highest and lowest points in the watershed (Fig. 1).

The Liusha River Watershed has a subtropical climate. The watershed is characterized by mountain ranges, steep slopes, and deep valleys (Xiang and Tang, 2006). The climate is dry and windy, and there is abundant annual sunshine. The average annual precipitation is 726 mm, of which 80%–90% falls during the monsoon season (June–September). The average annual runoff is 469 mm, the average annual sediment transport rate is 59.9 kg/s, and topsoil losses are as much as 2.9 million m^3/year. The valley area is the focus of agriculture in the watershed, and long-term soil erosion has resulted in decreases in soil fertility; ongoing land reclamation and human activities in the basin have resulted in severe soil degradation (Yang, 2012).

3. Methods

3.1. General study framework

Regression analysis was used to explore the impact of landscape patterns on soil erosion. The sub-basin was used as the analysis unit to ensure there was sufficient sample data. The soil erosion of each sub-basin was simulated using the SWAT model, which is a continuous-time, semi-distributed, process-based watershed scale model that was developed to predict the impact of land management practices on water, sediment, and chemicals (Arnold et al., 1998; Neitsch et al., 2011). The landscape metrics of each sub-basin were calculated with Fragstats version 4.0, a widely accepted tool for quantifying landscape indices (McGarigal et al., 2012). Multiple linear regression was used in Statistical Product and Service Solutions (SPSS) to fit the sample data, and then the implications of the regression equation were interpreted and discussed. Particular consideration was given to the following topics in this study:

(1) Soil erosion simulation

The ArcGIS-ArcView extension and graphical user input interface of SWAT, ArcSWAT, was used to establish and validate the distributed hydrological model of the Liusha River Watershed for runoff and sediment data from 1986 to 2005, and the soil for erosion of each sub-basin was simulated on the basis of land use maps that related to three different years (1986, 1995, and 2000). The erosion modulus (= erosion/area) was used to eliminate the influence of area on sub-basin soil erosion.

(2) Calculation of the sub-basin landscape pattern

The key landscape pattern metrics were selected at the landscape level, and then the landscape pattern indices of the three land use