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Partial least-squares regression for linking land-cover patterns to soil erosion and sediment yield in watersheds

Z.H. Shi [a,b,*], L. Ai [b], X. Li [b], X.D. Huang [b], G.L. Wu [a], W. Liao [c,d]

[a] State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Chinese Academy of Sciences, Yangling, Shaanxi 712100, China
[b] College of Resources and Environment, Huazhong Agricultural University, Wuhan 430070, China
[c] Huazhong Normal University, Wuhan 430079, China
[d] The Center of Soil and Water Conservation Monitoring, Hubei Province, Wuhan 430071, China

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SUMMARY

There are strong ties between land cover patterns and soil erosion and sediment yield in watersheds. The spatial configuration of land cover has recently become an important aspect of the study of geomorphological processes related to erosion within watersheds. Many studies have used multivariate regression techniques to explore the response of soil erosion and sediment yield to land cover patterns in watersheds. However, many landscape metrics are highly correlated and may result in redundancy, which violates the assumptions of a traditional least-squares approach, thus leading to singular solutions or otherwise biased parameter estimates and confidence intervals. Here, we investigated the landscape patterns within watersheds in the Upper Du River watershed (8973 km^2) in China and examined how the spatial patterns of land cover are related to the soil erosion and sediment yield of watersheds using hydrological modeling and partial least-squares regression (PLSR). The results indicate that the watershed soil erosion and sediment yield are closely associated with the land cover patterns. At the landscape level, landscape characteristics, such as Shannon's diversity index (SHDI), aggregation index (AI), largest patch index (LPI), contagion (CONTAG), and patch cohesion index (COHESION), were identified as the primary metrics controlling the watershed soil erosion and sediment yield. The landscape characteristics in watersheds could account for as much as 65% and 74% of the variation in soil erosion and sediment yield, respectively. Greater interspersion and an increased number of patch land cover types may significantly accelerate soil erosion and increase sediment export. PLSR can be used to simply determine the relationships between land-cover patterns and watershed soil erosion and sediment yield, providing quantitative information to allow decision makers to make better choices regarding landscape planning. With readily available remote sensing data and rapid developments in geographic information system (GIS) technology, this practical and simple PLSR approach could be applied to a variety of other watersheds.

1. Introduction

Soil erosion depends on the interaction of different physical and anthropogenic factors, including soil properties, topography, climatic characteristics, land use and its management. Soil properties and topography are relatively constant in the short term, and changes in land use and climate features are the dominant variables (Wei et al., 2007). Soil erosion is largely determined by the absence of protective land cover, whereas sediment export to rivers is determined by on-site sediment production and the connections between sediment sources and rivers (Bakker et al., 2008). The latter factor is also a function of land use because hydrological processes and sediment transport capacity vary for different types of land cover (Van Oost et al., 2000). The types of land cover are closely related to the characteristics of human activities, which in turn determine the anthropogenic substances carried into erosion systems through soil detachment, runoff process, sediment transport, and deposition. Previous studies have often focused on the composition of land cover within the watershed to explain variations in soil erosion and sediment yield (Phippen and Wohl, 2003; Pelacani et al., 2008; Casali et al., 2010; Feng et al., 2010; Nie et al., 2011; Yan et al., 2013). From a landscape ecology perspective, land cover patterns within the watershed may play a critical role in determining hydrological connectivity processes, the temporal storage of runoff and run-on,

* Corresponding author at: College of Resources and Environment, Huazhong Agricultural University, Wuhan 430070, China. Tel.: +86 27 87288249; fax: +86 27 87671035.
E-mail address: shizhihua70@gmail.com (Z.H. Shi).

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and sediment delivery. Therefore, understanding the relationships between land cover patterns and erosion processes is of practical importance for watershed planning and management.

Within the last few decades, the spatial configuration of land cover has become an important aspect of studies of geomorphological processes related to erosion (Valentin et al., 1999; Imeson and Prinsen, 2004; Ludwig et al., 2005; Puigdefábregas, 2005; Fu et al., 2009). The spatial configuration, including the extent, distribution, and intensity of land uses, is an important factor in understanding the erosion processes linking land use and sediment export. Bartley et al. (2006) reported large differences in the runoff and sediment yield measurements from three hill-slopes with similar total plant cover but different plant cover arrangements. The location of medium-to-high cover patches close to the bottom of hill-slopes, together with other co-occurring attributes such as topography and soil characteristics, were thought to determine the hydrologic response. Jordan et al. (2005) investigated the impact of historical land use changes on soil erosion and sediment transport using a modeling approach. Their results demonstrated that land use changes introduced by property ownership and agricultural changes have decreased sediment production in the catchment while increasing the relative sediment export to downstream areas within the basin. This increase in sediment export is due to changes in the land cover pattern that allow more sediment to be transported to the river system. Ziegler et al. (2007) quantified the effects of patchiness and the optimized patch arrangement of different land cover types to reduce runoff in two catchments in Vietnam. Independent of the modeled event size, increasing patchiness and an optimized patch arrangement, which maximizes the number of transfers between patches with different hydrologic behaviors, substantially reduced catchment outflow without changing the proportions of different land uses.

Land cover patterns can be described by using a variety of landscape metrics, and many different landscape metrics have been developed (Chen et al., 2008). As one of most important processes, soil erosion within a heterogeneous landscape has received significant attention. Not surprisingly, many studies have used multivariate regression techniques (a landscape metric approach) to examine the soil erosion and sediment yield response to different land cover patterns (Xiao and Ji, 2007; Lee et al., 2009; Ouyang et al., 2010; Huang et al., 2011; Memarian et al., 2012). Despite the great potential of these landscape metric approaches, they also present particular analytical challenges. Many landscape metrics are highly correlated, which can result in redundancy (Hargis et al., 1998). The use of correlated parameters violates the assumptions of the traditional least-squares approach, thereby leading to singular solutions or otherwise biased parameter estimates and confidence intervals. Therefore, significant caution must be exercised when using landscape metrics, particularly when establishing relationships between landscape patterns and ecological processes using these metrics (Corry and Nassauer, 2005; Chen et al., 2008; Yang et al., 2012). The inherent limitations of traditional multivariate regression approaches in handling multi-collinear and noisy data can be overcome by applying techniques based on multivariate statistical projection, such as principal component regression (PCR) and partial least-squares regression (PLSR). PLSR is a recent technique that combines features from the principal component analysis (PCA) technique and the multiple linear regression technique and generalizes them (Abdi, 2010). The PLSR technique handles highly correlated noise-corrupted data sets by explicitly assuming the dependency between variables and estimating the underlying structures, which are essentially linear combinations of the original variables (Carrascal et al., 2009; Singh et al., 2013).

We previously developed quantitative relationships between sediment yield and the compositions of land cover types within the Upper Du River watershed in China (Yan et al., 2013). However, spatial land cover patterns can exert a significant influence on runoff and sediment transport at different scales (Fu et al., 2009). The quantification of the effects of spatial land cover patterns on sediment yield is important to develop effective soil erosion control through spatial planning for land use. Therefore, for this study, the Upper Du River watershed was chosen as the case study area. The SWAT model and partial least-squares regression were used to explore the relationship between the watershed landscape characteristics and the soil erosion and sediment yield. The objectives of this study were to (i) investigate the relationship between the spatial configurations (landscape metrics) of land cover and the watershed soil erosion and sediment yield using partial least-squares regression at the sub-basin scale and (ii) model the sediment delivery ratio (SDR) using landscape metrics at the watershed level.

2. Materials and methods

2.1. Study area

The case study area is the Upper Du River watershed (31°30′N–32°27′N, 109°11′E–110°25′E), which is located in the Danjiangkou Reservoir Area and has a total drainage area of 8973 km^2 (Fig. 1). The Danjiangkou Reservoir on the Han River, the largest tributary of the Yangtze River, is the water source for the Middle Route Project under the South-to-North Water Transfer Scheme, and it supplies 13.8 billion m^3 of water annually to the North China Plain. This area has a typical subtropical monsoon climate. The average annual precipitation is approximately 973 mm, which mainly falls during the monsoon season (June–October), and the average yearly temperature is approximately 14.3 °C. The topography of the watershed is characterized by mountain ranges, steep slopes, and deep valleys, with altitudes of 220–2833 m. Forest is the principal land cover type in this watershed. The villages, small towns, and agricultural land are concentrated along the river. The major crops are corn (*Zea mays* L.) and wheat (*Triticum aestivum* L.).

2.2. Land-cover data and pattern analysis

Land cover maps for the years 1978, 1987, 1999, and 2007 were obtained from the Changjiang River Water Resources Commission (Fig. 2). The land use maps were generated from Landsat images, which were obtained from the Landsat archive (http://glovis.usgs.gov/). These images included Multi Special Scanner imaging for 1978, Thematic Mapper imaging for 1987 and 2007, and Enhanced Thematic Mapper imaging for 1999. The accuracy of the land cover types in the area was assessed before the data were released. The four-year land cover maps were prepared for use in the SWAT model and to calculate landscape metrics. Table 1 lists the information on the different land-cover types.

Although many landscape metrics have been proposed and utilized to quantify landscape patterns or characteristics, not all of these landscape metrics are informative for delineating patterns because of the multi-collinearity among the metrics and the erratic behavior of some of the metrics across different scales, such as the minimum mapping unit or the extent of the map (McGarigal et al., 2012). In this paper, 15 metrics were analyzed to describe the landscape features (Table 2). These selected metrics have been commonly used in previous studies of the role of land cover patterns in soil erosion or sediment yield (e.g., Ouyang et al., 2010; Huang et al., 2011; Wang et al., 2011; Memarian et al., 2012). These metrics reflect the major components of land use planning (i.e., shape, distance, connectivity, and diversity), which enable the results of this study to be readily applied to landscape and land use planning. Furthermore, these metrics are important in understanding the