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Effects of precipitation and restoration vegetation on soil erosion in a semi-arid environment in the Loess Plateau, China

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ABSTRACT

Soil erosion is a critical environmental problem of the Loess Plateau, China. As an important project for soil and water conservation in the semi-arid environment, the Grain-for-Green extensively transformed a wide range of farmland into vegetated land after the 1980s. Yet, the effects of vegetation restoration on soil erosion reduction are not well understood. In this study, we monitored runoff and sediment yield at sites restored with six typical restoration vegetation types including shrubs (*Armeniaca sibirica*, *Spiraea pubescens* and *Artemisia coparia*), grasses (*Andropogon*), and shrub–grass-compounds (*Andropogon* and *A. coparia*) in the Loess Plateau. We employed structural equation modelling (SEM) to systematically analyze the relative effects of precipitation and vegetation on soil erosion. The results showed that the runoff and sediment yield at the grasslands were significantly higher than other cover types. The shrub cover had the strongest soil conservation capacity of all restoration vegetation. SEM results showed varying impacts of precipitation (i.e., total amount and erosive rainfall intensity) on runoff and soil erosion under different vegetation types owing to differences in canopy structure and surface litter layer. Our study quantitatively revealed the interactive effects of precipitation and vegetation on runoff and sediment, which may be beneficial to conserving available water and soil resources in the semi-arid environment.

1. Introduction

Soil erosion is a serious and complex environmental problem worldwide (Portenga and Bierman 2011). It directly causes soil deterioration (Marques et al. 2008) and decreases land productivity (Lantican et al. 2003). It is mainly triggered by a combination of natural forces and anthropogenic activities. The eigenvalues of erosive precipitation and vegetation distribution patterns in a semi-arid environment are among the primary driving and preventive forces to soil erosion. Systematically comprehending the interactive effects of main influencing factors on soil erosion is a key step to conserve soil and water and assess the efficacy of soil erosion control practices in semi-arid regions (Fu et al. 2011).

Two typical conceptual models have been developed to represent the impacts of precipitation on runoff and sediment yield. The first kind of models emphasizes the role of the kinetic energy of erosive raindrops. Raindrops with kinetic energy that exceeds the threshold of soil erodibilitydetaches soil particles. The detached soil particles are the source of transportable sediments. In the revised universal soil loss equation (RUSLE), rainfall erosivity is an important contributing factor (Renard and Freimund 1994). This factor quantifies the kinetic energy of an erosive raindrop. The kinetic energy of erosive rainfall intensity was found to be the determinant of soil seal formation (Assouline and Ben-Hur 2006). The other type of conceptual models are built upon the formation of a soil seal after raindrop splashing which could effectively prevent infiltration and finally increase runoff.

On the other hand, vegetation has been widely reported to negatively correlate with runoff and sediment yield (Curran and Hession 2013; Fattet et al. 2011; García-Ruiz 2010; Gyssels et al. 2005; Puigdefábregas 2005). Vegetation type, spatial patterns, and their heterogeneous morphological characteristics in restoration land can have substantial impacts on soil erosion processes. Puigdefábregas et al. (1999) explored the importance of vegetated patches in minimizing soil erosion in semi-arid ecosystems. Plant spatial patterns can alter the source–sink erosion distribution, which was a precondition for describing the transporting route of runoff and sediment in a catchment or larger spatial scales (Bautista et al. 2007; Mayor et al. 2008; Puigdefábregas 2005). In a semi-arid environment, restoration vegetation with dense shrubs could effectively reduce runoff and sediment transport (García-Ruiz 2010). Forests showed the strongest ability to prevent soil erosion in the Loess Plateau (El Kateb et al. 2013). Some

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researchers (Burylo et al. 2011; Buttle and Farnsworth 2012; Fu et al. 2012; Mohammad and Adam 2010) observed that a mixed pattern of forests and shrubs would be optimal for inhibiting soil erosion.

The morphological properties of restoration vegetation play different roles on storing water and on controlling sediment yield. Interception (Ghimire et al. 2012; Wang et al. 2012) and absorption (Kurothe et al. 2014; Park et al. 2010) of throughfall are the substantial hydrological functions of canopy and litter layer in restoration vegetation. Wang et al. (2012) indicated the positive linear relationship between canopy storage capacity and leaf area index. Some interception models (Ghimire et al. 2012; Liu 1997; Liu 1998) explicitly use canopy structural information to quantify the complicated water balance related to canopy features. Canopy cover and plant height are two crucial variables that affect splash erosion in the Morgan–Finney model (Gu et al. 2013; Morgan 2001). Additionally, various litter layer types, including leaf residues (Geißler et al. 2012) and a vegetation ash layer (Cerdà and Doerr 2008), play crucial roles in protecting the soil against splash erosion and improving infiltration during precipitation (Price et al. 2010; Woods and Balfour 2010).

Although the effects of precipitation and vegetation on soil erosion in semi-arid environments have been extensively studied, complex interactions among these influencing factors remain unquantified (Curran and Hession 2013; Hartanto et al. 2003; Molina et al. 2012). More advanced analytical methods should be used to explore their direct and indirect impacts and relative contributions to soil and water loss. Comparing with other multivariate analytical methods, structural equation modelling (SEM) is constructed on the complete body of specific and available knowledge (Grace 2006). The problem-oriented property of SEM combines concrete a priori knowledge with statistical analysis, and effectively estimates the strength of direct or indirect effects of multi-variables on the responses. Moreover, it could specifically determine the causal relationships between potential independent variables and responsive variables and consequently systematically examine the interactive effects of contributing factors exerting on the responsive results (Grace 2006). SEM has been applied to deal with many complex and challenging problems in ecological studies (Austin 2007; Larson and Grace 2004; Sutton-Grier et al. 2010; Texeira et al. 2012), but with few applications to study soil erosion problems (Chamizo et al. 2012).

In this paper, we monitored soil erosion under different heterogeneous restoration vegetation patterns in the Loess Plateau during a 4-year period. We further employed the univariate regression and SEM methods to analyze the interactive effects of main influencing factors on runoff and sediment. The aims of this study were to: (1) estimate the variance of runoff and sediment response to vegetation type, (2) determine the contributions of precipitation and vegetation on soil erosion, and (3) partition and explain which factors are the most important in affecting erosive response in each of three vegetation types.

2. Materials and methods

2.1. Site description

The study was conducted in the Yangjuangou Catchment (36°42'N, 109°31'E, 2.02 km^2) in the central part of the Loess Plateau (Fig. 1A). The climate is typical semi-arid with an average annual rainfall of 535 mm. There is an obvious rainy season from June to September with precipitation indicating significant inter-annual variability. Soil type is classified as Calcaric Cambisol whose weak structure is

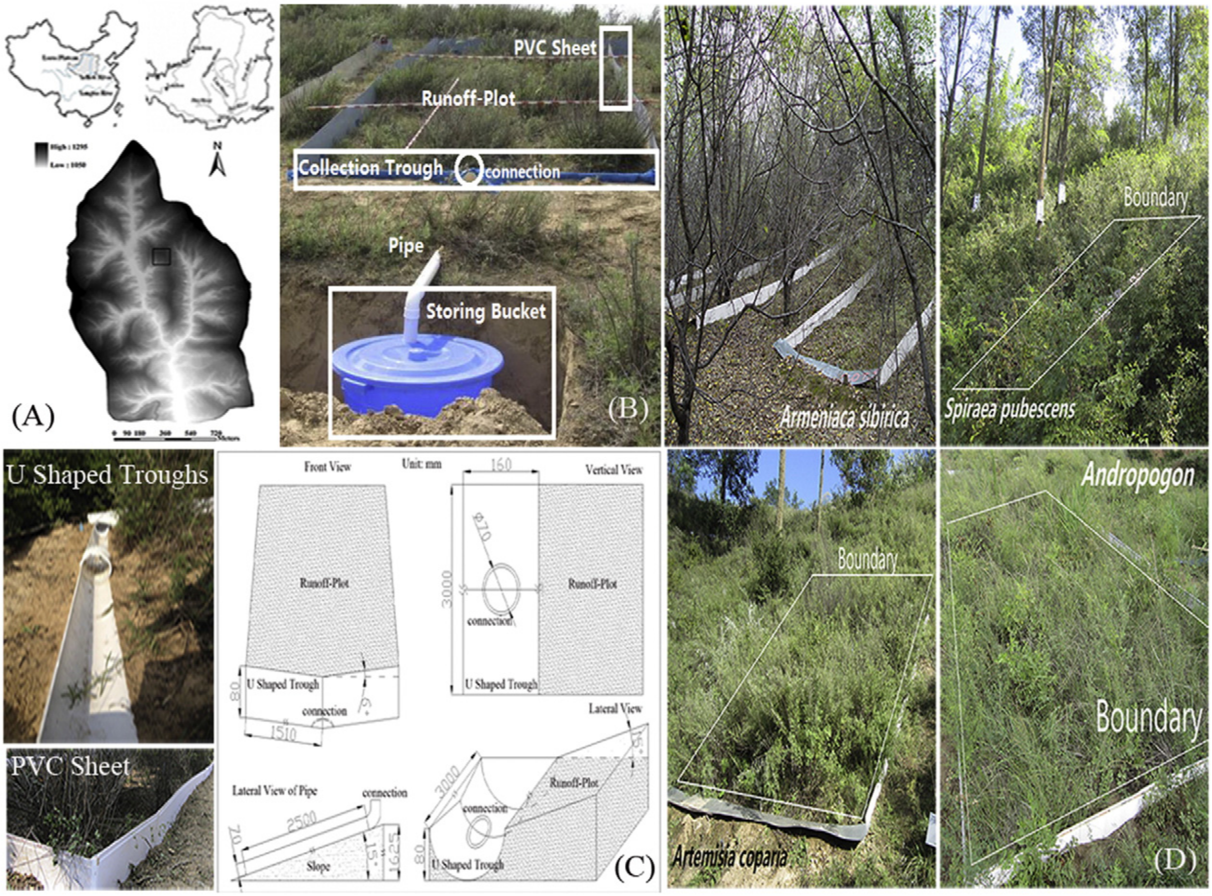

Fig. 1. The location of study region (A), runoff-plot system (B), sketch of collection–transmission system with specific size annotation (C), and restoration vegetation types in all runoff-plots (D).