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Spatial heterogeneity of microtopography and its influence on the flow convergence of slopes under different rainfall patterns

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ABSTRACT

This study aimed to reveal the spatial heterogeneity of the microtopography and its influence on flow convergence on sloping farmland of purple soil area in China. Methods involving artificial rainfall, pin meter and photographic measurements were adopted to generate DEM (digital elevation model). Geographic statistics and multifractal theory were used for quantitative and hydrological analyses of microtopography based on ArcGIS. Two artificial tillage practices (ridge tillage and conservation tillage) were used to simulate different types of microtopography. Ridge tillage (RT) was designed according to local agricultural customs in China, with conservation tillage (CK) used for comparison purposes. A total of 12 rainfall simulation experiments were conducted in two 1 m by 2 m boxes under increased rainfall series (1.0, 1.5, and 2.0 mm min^{-1}) and decreased rainfall series (2.0, 1.5, and 1.0 mm min^{-1}) on a typical slope gradient of 15°. Artificial tillage was the major contributing factor to the spatial heterogeneity of microtopography on sloping farmland of the purple soil area. Spatiotemporal variability of microtopography was expressed using semivariogram and multifractal spectrum, and spatial heterogeneity of drainage networks was expressed using general fractal dimension ΔD based on multifractal theory. In general, the drainage networks was mostly effected by microrelief. The drainage density of ridge tillage was smaller than that of the conservation tillage under different rainfall patterns, and the drainage density decreased remarkably with the increasing microrelief. Moreover, the ΔD values of ridge tillage ranged from 0.1817 to 0.5677. By contrast, the ΔD values of the conservation tillage ranged from 0.9662 to 1.3013, and thus the lower spatial heterogeneity of drainage networks in ridge tillage compared to conservation tillage. In this study, we established a novel method for analysis of the spatial heterogeneity of microtopography and demonstrated the effect of microtopography on the flow convergence of sloping farmland. These findings had important implications for clarifying the essence of microtopography of purple soil area and laying a theoretical basis and a support datum for harnessing measure of sloping farmland.

1. Introduction

Microtopography is the undulating surface configuration which has fewer changes in the relative elevation in a relatively small place (Zhang et al., 2014), that affects not only surface hydrological and hydraulic characteristics (Yang and Chu, 2013; Peñuela et al., 2015), but also penetration rate (Morbidelli et al., 2015), surface runoff (Rai et al., 2010; Vermang et al., 2015), surface depression storage (Planchon and Darboux, 2002), and transition and deposition of soil particles during water erosion process (Shi et al., 2012; Wang et al., 2014). In contrast, these processes also affect the spatial distribution of microtopography. Previous studies on microtopography mainly focus on influencing factors, measuring methods (Burwell et al., 1963; Saleh, 1993; Darboux and Huang, 2003; Haubrock et al., 2009), and the relationship between microtopography and soil erosion (Zhao et al., 2015). However, the evolution of spatial and temporal variability in the soil erosion process on a microtopographic scale is poorly studied due to the random nature of microtopography in the process of erosion and technical limitations of measurement. Knowledge about microtopography and erosion mechanism at the microtopographic scale fell behind that of soil and water conservation required in practice (Zhang et al., 2014).

The main factor affecting hydrological processes is topography, which determines the flow direction and drainage networks (de Azeredo Freitas et al., 2016). Hydrological characteristics may reflect indirectly the topography and landform characteristics.

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Therefore, analyzing the relationship between hydrological and topographic features can be an effective approach for probing soil erosion. The similarity and regularity of drainage networks is accepted widely (Martz and Garbrecht, 1993; Jenson and Domingue, 1988), and thus the principle of river basin scale can be applied to the slope scale. However, the mentioned research is limited to the smooth soil surface (Qin et al., 2013), and drainage networks on slope farmland is obviously controlled by two-dimensional variation (Souchere et al., 1998). The microtopography on sloping farmland generated by human management is not only the direct result of slope erosion but also the principal factor leading to the further development of slope erosion (Zhang et al., 2014). At present, studies on the influence of tillage practices on the development of drainage networks on slope are relatively few (Moussa et al., 2002). A description and explanation, as well as modeling of the evolution process for flow convergence on a slope will further improve our knowledge on soil erosion.

Ridge tillage is common agricultural practice throughout the world (Lal, 1990; Müller et al., 2009). Ridge tillage, in which seedbed is raised above the natural terrain, has distinctive advantages, such as increasing soil temperature, saving labor, enhancing soil depth, and controlling pests and weeds (Gupta et al., 1990; Hatfield et al., 1998; Shi et al., 2012). However, the impact of ridge tillage on soil erosion remains controversial. Some research indicated that ridge tillage can reduce soil and water loss (Zhang et al., 2014). However, other studies suggested that ridge tillage may even accelerate soil erosion because variations in field slope and microtopographic relief can produce ineffective erosion control (Liu et al., 2014, 2015). Such differences may be due to spatial heterogeneity of microtopography in the process of water erosion.

Geo-statistical analysis of spatial variability has been extensively used and documented at different scales, including soil surface microrelief plots characterized by point elevation measurements (Vázquez et al., 2010). On the one hand, geostatistics can effectively reveal the spatial distribution and correlation of a system property in a given space (Negre et al., 2016; Kumar and Singh, 2016). On the other hand, the spatial pattern of variables can be linked to the erosion processes (Giménez et al., 2016). The fractal dimension method is used to interpret complex spatial structures and to quantitatively characterize the uniformity of spatial objects. Simple fractal dimension mainly relies on average processing and approximate analysis, which cannot provide comprehensive information, whereas multifractal analysis (MFA) has been proposed as an extension of simple fractal dimension to describe more sophisticated, structured objects on different scales. Many studies demonstrated that MFA is a powerful tool for dealing with nonlinear and complex systems (Moreno et al., 2008; Vázquez et al., 2010; Zhang et al., 2012; Li et al., 2015; Medina-Cobo et al., 2016). Microtopography can be considered to be a lively place which can reflect diverse elements of slope erosion kinetics as well as their interaction (Kirkby, 2002). The present research aimed to analyze the spatial heterogeneity of microtopography on different rainfall patterns and its influence on flow convergence of a slope under laboratory conditions. Results of this study provide important information on soil erosion at centimeter scale, which would improve the application of tillage practices in terms of soil and water conservation.

2. Materials and methods

2.1. Soil experiments

Soil was collected from the top 20 cm of a soil profile on sloping farmland in the upper reaches of the Huajiao River, Songtao, Ziyang in the Tuo River system of the Yangtze River (104°34′12″–104°35′19″E and 30°05′12″–30°06′44″N) with an elevation of 395 m. The area is dominated by purple soil formed in the Purple sandy shale, classified as Entisol according to the soil taxonomy of the U.S.D.A. (Soil Survey Staff, 1999). Soil physical-chemical property was listed in Table 1. Two iron boxes (2.0 m × 1.0 m × 0.5 m) were used in the rainfall simulation study. Air-dried top soil was passed through a 10 mm sieve and the sieved soil was thoroughly mixed to minimize differences among the treatments. Each soil box was filled with 10 cm layers of soil to a depth of 50 cm and each soil layer was raked gently before packing the next layer to ensure uniformity and continuity in the soil structure. The amount of soil in each layer was kept as constant as possible to maintain a consistent bulk density and uniform spatial distribution of soil particles among layers (An et al., 2012). The soil bulk density was controlled at 1.2 g cm^{-3} to ensure homogeneity resemble natural state through randomization. The soil bulk density was measured by a ring sampler (ISSAS, 1978).

2.2. Rainfall simulation

The simulated rainfall experiments were conducted at the Soil Erosion Research Laboratory, Sichuan Agricultural University. The rainfall simulator was programmed and equipped with two spray nozzles. The nozzles were the V-80100 series and was introduced from the Institute of Soil and Water Conservation, Chinese Academy of Sciences. Operating pressure ranged from 0 to 1.0 bar. Rainfall simulator height was 6.5 m and effective rainfall area was approximately 48 m^2. The rainfall uniformity of the simulator was approximately 85%. The sloping farmland gradient of purple soil area is generally between 10° and 20°, and 15° is representatives of the main slope gradients in the study area (Chen et al., 2015). The soil box was adjusted to a 15° slope and then placed under a rainfall simulator. The simulated rainfall intensities were 1.0, 1.5, and 2.0 mm min^{-1} according to the characteristic of local storms which were concentrated in summer and autumn of the study area. The rainfall duration was 60, 40, and 30 min respectively to ensure the amount of rainfall consistency in each rainfall event. The simulated rainfall was divided into increased rainfall series and decreased rainfall series to reflect the natural rainfall. For increased rainfall series, the first rainfall event was performed with 1.0 mm min^{-1} rainfall intensity and 60 min durations, the second rainfall event was performed with 1.5 mm min^{-1} rainfall intensity and 40 min durations, and the third rainfall event was performed with 2.0 mm min^{-1} rainfall intensity and 30 min durations. For decreased rainfall series, the first rainfall event was performed with 2.0 mm min^{-1} rainfall intensity and 30 min durations, the second rainfall event was performed with 1.5 mm min^{-1} rainfall intensity and 40 min durations, and the third rainfall event was performed with 1.0 mm min^{-1} rainfall intensity and 60 min durations. In order not to impact the determination of soil microrelief, there was 24-h interval between rainfalls. Soil surface covered with plastic film to avoid the influence of evaporation during the experimental period. Ridge tillage was horizontal tillage in the direction which was perpendicular to the slope with a ridge height of 15 cm and ridge width of 40 cm according to local agricultural customs in purple soil area, with conservation tillage (CK) used for comparison purposes. They were used to simulate different types of microtopography.

Table 1
Physical-chemical property of experimental soil.

pH	Bulk density (g cm^{-3})	Sand (%)	Silt (%)	Clay (%)	Texture
7.5	1.20	49	29	22	Clay loam