Catena xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Changes of soil microrelief and its effect on soil erosion under different rainfall patterns in a laboratory experiment

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ARTICLE INFO

Keywords:
Soil microrelief
Multifractal analysis
Surface runoff
Sediment yield
Simulated rainfall
Laboratory experiments

ABSTRACT

Soil microrelief has been found to influence processes of water infiltration, runoff and erosion. However, its mathematical description remains poorly understood. The primary objective of this study was to explore changes in soil microrelief and its effect on surface runoff and sediment yield. The associated experiments were based on multifractal analysis (MFA) under a simulated rainfall series in a laboratory located in the purple hilly area of Sichuan, China. A total of 12 rainfall simulation experiments were conducted in two 1 m by 2 m boxes under 2 rainfall series, including an increased rainfall series (60 mm·h^{-1}, 90 mm·h^{-1} and 120 mm·h^{-1}) and a decreased rainfall series (120 mm·h^{-1}, 90 mm·h^{-1} and 60 mm·h^{-1}) on a 15° slope. The results indicated that decentralized depressions were formed in the middle and lower slopes after the first rainfall event, while rills were gradually formed under the increased rainfall series. Under the decreased rainfall series, obvious rill erosion appeared following the first rainfall event. Under increasing rainfall intensity, the change of soil roughness index (R) is in the range of 75.99–79.29, and the roughness index (R) of the middle and lower slopes exhibited a gradually increasing trend, and the R of the lower slopes was noticeably higher than the middle slopes. Under the decreased rainfall series, the change of R was in the range of 77.65–79.80, the R of the middle and down slopes did not exhibit an obvious change during rainfall period. The soil microrelief indicated multifractal characteristics under the different rainfall series. Under an increased rainfall series, the fractal dimension span (ΔD) and singular index span ($\Delta\alpha$) showed a gradually increasing trend, while an opposite trend was exhibited under the decreased rainfall series. The R and singular index span ($\Delta\alpha$) were positively correlated with ΔD. Compared with R, $\Delta\alpha$ reflected the changes in soil microrelief for the entire spatial structure. The surface runoff volume of the increased rainfall series was only 5.82% higher than that of the decreased rainfall series, and the total sediment yield in the former was 35.83% higher than that of the latter. The use of multifractal parameters of soil microrelief to forecast sediment yield was deemed to be feasible.

1. Introduction

Soil erosion is a frequently occurring environmental issue, compromising sustainable development across a multitude of economies and societies globally (Feng et al., 2010). Soil surface characteristics including soil microrelief, cohesion and granular stability are primary factors influencing erosion and runoff processes, and of these characteristics, soil microrelief is a significant parameter (Gómez and Nearing, 2005; Mirzaei et al., 2008). Soil microrelief describes the variation in surface elevation across a field and constitutes the spatial arrangement of microtopographic variation in soil surface elevation at scales ranging from centimetres to millimetres or less (Vidal Vázquez et al., 2005; Paz-Ferreiro et al., 2008). Soil surface roughness (SSR) is expressed as the change in height in respect to the overall shape of the soil microrelief (Darboux et al., 2001). SSR has been demonstrated to influence water infiltration, splashing quantity, overland flow and runoff routing (Govers et al., 2000; Römkens et al., 2001; Gómez and Nearing, 2005). Kuipers (1957) first introduced the standard deviation of the elevation readings of the soil surface to describe SSR. Subsequently, other well-known indices have been proposed including the random roughness index (Allmaras et al., 1966), MIF index (Römkens and Wang, 1986), limiting slope (LS) and limiting difference (LD) indices (Linden and Van Doren, 1986), and the roughness index of Saleh (1994), etc. In addition, some researchers have presented empirical equations of SSR based on regression analysis between hydraulic resistance characteristic parameters and roughness indexes (Gilley and

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https://doi.org/10.1016/j.catena.2017.11.010
Received 27 May 2017; Received in revised form 4 October 2017; Accepted 3 November 2017

Finkner, 1991; Mwendera and Feyen, 1992; Weltz et al., 1992; Abrahams et al., 1994). However, SSR remains poorly defined and is most often described in terms of empirical indices, as the association of the soil structural units in the formation of the surface microrelief has not been simple to quantify (Vidal Vázquez et al., 2005).

Numerous studies since the 1960s have prioritized issues relating to soil erosion, including SSR formation, methods of measurement, the interaction of SSR and soil erosion, and slope-related hydrological processes (Huang et al., 1988; Favis-Mortlock, 1998; Abell et al., 2008; Martin et al., 2008; Zheng et al., 2014). At the field and catchment scale, SSR can influence the organization of drainage patterns, significantly impacting the spatial distribution of sediment sources and sinks. Additionally, several of these processes precipitate changes in soil microrelief. Furthermore, soil microrelief is not static, with the result that previous studies on SSR and soil erosion have produced inconsistent results (Lima and Abrantes, 2014). Some studies have suggested that the water-holding capacity and infiltration rate of the soil surface is indirectly influenced by SSR (Hansen et al., 1999; Kamphorst et al., 2000; Planchon et al., 2002) and reduces overland flow, which in turn reduces the erosive capacity of runoff (Gómez et al., 2009). However, some researchers have suggested that SSR may increase the soil erosive capacity (Römkens et al., 2001; Gómez and Nearing, 2005). Processes of soil microrelief and runoff erosion are interconnected (Favis-Mortlock, 1998), and thus unravelling the dynamics of SSR is necessary for an enhanced understanding of soil erosion. However, the random nature of SSR in the erosion process, as well as the technical limitations of previous ground measurements, poses certain challenges. As a result, few studies have investigated the changes in spatial variability of the soil erosion process at a microtopographic scale.

As fractal theory can be used to analyse the associations between soil structure and other soil parameters, it acts as both a predictive and descriptive tool in soil science (Su et al., 2004). With the aid of fractal parameters, a unified conceptual framework has been established in SSR analysis for describing the geometric complexity of data. Several methods have been developed for the estimation of fractal dimensions of soil microtopography (Malinverno, 1990; Perfet and Kay, 1995; Vidal Vázquez et al., 2005, 2006). However, a statistical index and simple fractal dimension can characterize the general features of microtopography (Zhao et al., 2010), but cannot reflect its local features. Manninen (2003) showed that bare soil exhibits multiscale behaviour, and Roisin (2007) showed that MFA can effectively analyse the variability in the inner heterogeneity. Multifractal analysis may be an effective means of obtaining numerical data on the effect of surface topography on a microtopographic scale, and has been widely applied in geomorphology or digital terrain heights (Pike, 2000; Paz González et al., 2000), as well as in studies of soil erosion (Huang and Bradford, 1992; Li et al., 2009). Microtopographic spatial variability characterization is necessary for understanding diverse hydrological processes, as well as for improving the modelling accuracy of processes relevant to conservation planning at a given scale (Pandey and Pandey, 2010). Accurate descriptions of soil microrelief are therefore also essential for modelling erosive processes (Favis-Mortlock et al., 2000; Takken et al., 2001).

Many physical processes are known to operate on soil at a variety of scales, resulting in structures that appear to vary in a fractal manner (Armstrong, 1986; Vidal Vázquez et al., 2005). More realistically, these probably comprise short-range “multifractals”, constituting a partition of fractal domains and dimensions for different parts of the system (Burrough, 2001; Roisin, 2007). While an SSR-related study has been reported from the Loess Plateau of China (Zhao et al., 2014), none have focussed on the purple hilly area of Sichuan, China. Additionally, as a result of the random nature of soil microrelief in the process of erosion, as well as the technical limitations of previous ground measurements, few studies have detailed the evolution of spatial variability with respect to water erosion on a micro-scale. This has significantly hindered our comprehension of the role of soil microrelief in the soil erosion process. The objectives of this study were (1) to provide an additional means of describing the spatial distribution and change characteristics of soil microrelief under different rainfall series; (2) to use a statistical parameter (roughness index) and multifractal parameters to describe the soil microrelief in a laboratory experiment; and (3) to evaluate the effect of soil microrelief on runoff and sediment yield.

2. Material and methods

2.1. Study area and soil sampling

Soil samples were collected from the upper reaches of the Huajiao River in the Songtao region near Ziyang, in the Tuo River system of the Yangtze River, Sichuan Province, China (104°34′12″–104°35′19″E and 30°05′12″–30°06′44″N). The area is situated in a typical hilly region at a mean altitude of 425 m. The climate of the region is subtropical monsoon with an average temperature of 16.8 °C and rainfall in excess of 966 mm per annum. Precipitation falling between July and September accounts for 70% of the total annual rainfall.

Soil was sampled at a depth of between 0 and 20 cm on a sloped surface at a gradient of 15° on land that had been subjected to continuous cultivation for > 30 years. Purple soil formed from purple sandy shale constituted the dominant soil type of the area. The soil could be classified as an entisol according to the soil taxonomy of the USDA (Soil Survey Staff, 1999), which usually occurs at a depth of between 50 and 80 cm and is characterized as possessing a relatively light texture and poor soil fertility. The results of soil basic properties are as follows: organic matter of 8.25 g kg^{-1}, total N of 0.73 g kg^{-1}, available N of 108 mg kg^{-1}, available P of 18.7 mg kg^{-1}, and available K of 71 mg kg^{-1}. The particle size distribution contains 22% of clay, 29% of silt, and 49% of sand.

2.2. Soil box

The rainfall simulation study utilized 2 iron boxes (2.0 m × 1.0 m × 0.5 m) into which holes were drilled into the bottom of the flume to facilitate unrestricted drainage. A 10-cm-thick filtration layer of coarse sand was placed above the holes. To ensure homogeneity, the soil sample was sieved through a 10-mm mesh and placed into each erosion box to an area of 2 m^2. The soil surface of the 2 soil boxes was flattened for consistency prior to each rainfall event. The soil bulk density was controlled at 1.2 g cm^{-3} through a randomized process to ensure that it resembled the natural soil state, and the soil water content was adjusted to 10% prior to the rainfall events. The soil bulk density was measured by means of a ring sampler (ISSAS, 1978).

2.3. Rainfall simulation experiments

The rainfall simulation experiments took place in the soil erosion laboratory of the Sichuan Agriculture University in Chengdu, China. The soil box was adjusted to a 15° slope and then subjected to a rainfall simulator that had been programmed and equipped with 2 V-80100 series spray nozzles (SR), introduced by the Institute of Soil and Water Conservation (USA), Chinese Academy of Sciences and Ministry of Water Resources. The orifice diameter of the nozzles was 6.4 mm and the spray was angled from approximately 45° to 60°. The operating pressure ranged from 0 to 5.0 bar and the rainfall intensity was calibrated using the changes in operating pressure. The height of the rainfall simulator measured 7 m, with the entire effective rainfall area measuring approximately 30 m^2. The height point of reference constituted the lowest point of the soil surface, and within the effective rainfall area the rainfall uniformity of the simulator reached approximately 90%. In this study, the designated rainfall intensities were 60, 90 and 120 mm·h^{-1}. Rainfall intensity was monitored during each rainfall simulation using 5 rain gauges located on the soil box edges. To reflect the natural rainfall process, the simulated rainfall was divided