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Developing equations to explore relationships between aggregate stability and erodibility in Ultisols of subtropical China

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ABSTRACT

A soil aggregate represents a key soil structural unit that influences several physical soil properties such as water infiltration, runoff and erosion. The relationships between soil aggregate stability and interrill and rill erodibility are critical to process-based erosion prediction models yet remain unclear, likely due to the difficulty of distinguishing between interrill and rill-eroded sediment during the erosion process. This study was designed to partition interrill and rill erosion rates and relate them to the aggregate stability of Ultisols in subtropical China. Six kinds of rare earth elements (REEs) were applied as tracers mixed with two cultivated soils developed over Quaternary red clay or shale at six slope positions. Soil aggregate stability was determined by the Le Bissonnais (LB)-method. Simulated rainfall of three intensities (60, 90 and 120 mm h^{-1}) was applied to a soil plot (2.25 m long, 0.5 m wide, 0.2 m deep) at three slope gradients (10°, 20° and 30°) for a duration of 30 min after runoff initiation. The results indicated that rill and interrill erosion rates in the soil developed over shale were considerably greater than those in the soil developed over Quaternary red clay. Equations using an aggregate stability index A_s to replace the erodibility factor of interrill and rill erosion in the Water Erosion Prediction Project (WEPP) model were constructed after analysing the relationships between estimated and measured rill and interrill erosion data. The results show that these equations based on A_s have the potential to improve methods for assessing interrill and rill erosion erodibility synchronously for subtropical Ultisols by using an REE tracing method.

1. Introduction

Ultisols, locally known as red soils, occupy approximately 1.14 million km^2 of southeastern China. Improper land use and poor soil management have caused severe soil losses from water erosion in the region (Liang et al., 2010) resulting in the complete loss of the A and/or B horizons, and leaving the plinthic C horizon exposed in numerous areas of southern China (Deng et al., 2010).

Process-based erosion models applied to agricultural soils usually rely on the rill-interrill concept, which requires different relationships and algorithms (Nearing et al., 1989; Laflen et al., 1991) for each component. Rill erosion occurs due to the detachment and transportation of particles and aggregates by concentrated flow, whereas interrill erosion occurs between rills because of the combined effects of raindrop impact and shallow overland flow. Soil erosion prediction is a complex process affected by several factors. Soil erodibility, K_i for interrill erosion and K_r for rill erosion, is regarded as a key parameter for evaluating a soil's susceptibility to erosion and is essential for predicting soil loss and evaluating the environmental effects thereof (Wang et al., 2013). Both K_i and K_r can be determined either by data from experimental plots (Truman and Bradford, 1995; Zhang et al., 2003; Wang et al., 2012) or from soil properties, including soil texture, cohesion strength, soil shear strength, clay content and aggregate stability (Wang et al., 2013).

Among the aforementioned properties, aggregate stability, is a key soil structural trait that describes the resistance of aggregates to the disintegrating action of water (Valmis et al., 2005). Aggregate stability has an enormous influence on soil erosion (Barthès and Roose, 2002; Dimoyiannis et al., 2006; Ding and Zhang, 2016). For instance, rill erosion in soils with large aggregate stability is less than that in soils with low aggregate stability (Zheng et al., 1989). The ability of topsoil aggregates to resist erosion is reportedly a valuable indicator of field-assessed runoff and interrill erosion of sandy loam soils (Cantón et al., 2009). Previous studies have established formulas to describe the relationship between interrill erosion and topsoil aggregate stability, which is reflected through different indicators, such as percolation

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stability (*PS*) (Mbagwu and Auerswald, 1999) and aggregate instability (β) (Valmis et al., 2005; Dimoyiannis et al., 2006). Both *PS* and β mainly simulate the fast wetting effect, which is a major influence on aggregate destruction. These parameters can partially explain the relationship between interrill erosion and topsoil aggregate stability. However, the mechanisms primarily responsible for aggregate breakdown during water erosion processes include both slaking by fast wetting and mechanical breakdown due to raindrop impact (Shi et al., 2012). Mechanical breakdown due to raindrop impact is another important sub-process of interrill erosion.

The stability index, A_s, is probably a better aggregate indicator for slaking by fast wetting and mechanical breakdown due to raindrop impact effects (Yan et al., 2008; Shi et al., 2010). A_s was used by Yan et al. (2008) and Shi et al. (2010) to replace K_i in the interrill erosion equation of the Water Erosion Prediction Project (WEPP) model. Wang et al. (2012) discovered that A_s was also closely related to the soil detachment rate and was linearly correlated with the concentrated flow erodibility factor (K_r) under scouring conditions ($R^2 = 0.70$, $p < 0.01$). That study proposed using A_s to in place of K_r in the rill erosion equation of the WEPP model. Thus, A_s can be used to express both K_i in the interrill erosion equation and K_r in the rill erosion equation of the WEPP model. However, interrill and rill erosion are continual and simultaneous processes on slopes with rill present (Song et al., 2003). For the purposes of accurately describing the erosion process and calculating the relative contributions of interrill and rill erosion, it is necessary to determine the relationships between K_i, K_r and A_s simultaneously during rainstorms.

Conventional erosion monitoring techniques such as field plots (Stefano et al., 2013) and stereo-photo-surveys (Nachtergaele and Poesen, 1999), cannot readily distinguish between interrill- and rill-eroded sediments. Numerous methods have been applied in recent decades for distinguishing interrill- and rill- eroded sediments in experimental plots using tracers, e.g., beryllium-7 (Yang et al., 2006; Liu et al., 2011), glass particles (Young and Holt, 1968), artificial radionuclides (^{134}Cs & ^{60}Co) (Greenwood, 2012) and REEs (Zhang et al., 2001; Song et al., 2003; Liu et al., 2004). The exact proportion of the fallout beryllium-7 inventory that reaches the soil surface can be greatly spatially variable due to uptake by vegetation, which is highly variable and depends on vegetation density and length (Mabit et al., 2008; Greenwood et al., 2014). Fluorescent dyes incorporated into glass particles have previously been used in soil erosion studies (Young and Holt, 1968). However, glass particles differ in their size distribution, particle density, shape, surface morphology and surface chemical properties from soil particles and aggregates such that they may not bind well to the soil particles and aggregates and therefore get transported separately (Zhang et al., 2001). REEs are found at low background concentrations in soils, chemically stable, environmentally safe and undergo low plant uptake. REEs therefore make ideal soil tracers because they also strongly adsorb to soil particles without interfering in their movement and can be analysed readily and accurately (Mahler et al., 1998; Zhang et al., 2001). They have been widely applied in research on erosion processes, particularly for tracing sediment sources and sediment movement from slopes and watersheds (Tian et al., 1994; Matisoff et al., 2001; Song et al., 2003; Liu et al., 2004; Kimoto et al., 2006; Polyakov and Nearing, 2004; Polyakov et al., 2009; Liu et al., 2016a, 2016b). Since interrill erosion generally occurs from the upper 10 mm of soil (Xue et al., 2004; Liu et al., 2011; Greenwood, 2012), REEs applied at different depths have the potential to distinguish interrill and rill erosion during rainstorms K_i and K_r can then be estimated simultaneously.

Against this background information, the purposes of this study were (i) to partition interrill and rill erosion for Ultisols using REEs as tracers during simulated rainstorms; (ii) to develop new equations for predicting both interrill and rill erosion rates that incorporate relevant soil aggregate stability indices to replace the erodibility factors; and (iii) to validate the newly developed equations.

2. Materials and methods

2.1. Study area

Soils developed over Quaternary red clay or shale, classified as Ultisols (Soil Survey Staff, 2014), were collected from Xianning County (29°39′–30°02′ N and 114°06′–114°43′ E) and Yidu City (30°05′–30°35′ and 110°05′–111°35′ E). Xianning and Yidu are located in the southeast and southwest of Hubei province, China, respectively, and are characterized as having a subtropical monsoon climate. The annual average precipitation and temperature in Xianning and Yidu are 1577 mm and 16.8 °C and are 1600 mm and 16.7 °C, respectively. Rainfall intensities exceeding 50 mm h^{-1} in this area are common (Shi et al., 2010). Samples collected from the uppermost 30-cm layer comprise 58.3% clay, 32.5% silt and 9.2% sand for the soil developed over Quaternary red clay (clay soil) and 21.5% clay, 38.3% silt and 40.2% sand for the soil developed over shale (loam soil). The bulk density and organic matter content for soil developed over Quaternary red clay were 1.16 g cm^{-3} and 1.5%, respectively, and 1.25 g cm^{-3} and 1.7% for soil developed over the shale.

2.2. Experimental design

All soil samples used in the experiment were air-dried and screened through a 2-mm sieve. Six REE oxides in powder form (Yb_2O_3, Tb_4O_7, Sm_2O_3, CeO_2, La_2O_3, Dy_2O_3) were chosen for this study based on their price, quantity to be applied, and susceptibility to detection (Xue et al., 2004). The concentrations of the background and applied REEs in the experiment are shown in Table 1.

Each REE oxide was initially mixed thoroughly with 1 kg of air-dried soil and then mixed with additional air-dried soil approximately five times until it reached the target application concentration. Soil samples, each containing a corresponding REE, were prepared for packing into metal plots with dimensions measuring 2.25 m in length, 0.5 m in width, and 0.2 m in depth as depicted in Fig. 1. The plot was subdivided into three equal parts of length 75 cm each. The plots were set at 10°, 20° and 30°. Packing was carried out layer by layer to achieve the desired uniform mean bulk density (1.16 g cm^{-3} for the soil developed over Quaternary red clay and 1.25 g cm^{-3} for the soil developed over shale). Erosion within the depths of 0.0–1.0 cm and 1.0–20.0 cm was deemed to be interrill and rill erosion, respectively (Xue et al., 2004; Liu et al., 2011; Greenwood, 2012). Thus, six areas with different REEs were existing as shown in Fig. 1. The bottoms of the plots were perforated and covered with a 20 cm layer of sand to facilitate even drainage of percolating soil water. Runoff was funnelled to a collection vessel placed at the lower end of the plot. After packing, the surface soil was watered to saturation, covered with a rain shelter and maintained for three days without any disturbance to enhance the adsorption of the REEs to soil particles.

Three rainfall simulations, with intensities of 60, 90 and 120 mm h^{-1}, were conducted for 30 min following the initiation of runoff. These intensities were based on the natural maximum rainfall

Table 1
Background and applied REEs concentrations in the experiment.

Element	La_2O_3	CeO_2	Sm_2O_3	Tb_4O_7	Ho_2O_3	Yb_2O_3
Background concentration in the soil developed over Quaternary red clay (mg·kg^{-1})	25.86	49.42	1.73	0.45	0.42	1.29
Background concentration in the soil developed over shale (mg·kg^{-1})	15.46	32.66	2.48	0.31	0.31	0.93
Applied concentration (mg·kg^{-1})	773.00	489.90	124.00	11.63	18.60	18.60