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Splash detachment and transport of loess aggregate fragments by raindrop action

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ABSTRACT

Splash erosion, which results from the bombardment of raindrops on soil, is the initial stage of soil erosion by water and is mainly responsible for the detachment and transport of soil aggregates. The objective of this study was to estimate the difference between the breakdown and dispersion of soil aggregates for two typical soils (Lou soil and Drab soil) of the Loess Plateau by raindrop action and to determine the relation between raindrop size and splash distance as well as soil aggregate detachment and transport in the loess area. Simulated tests were performed using a custom-made device to generate raindrops of six different sizes (2.67 mm, 3.05 mm, 3.39 mm, 3.79 mm, 4.05 mm and 5.45 mm) and to measure splash erosion at five distance intervals (0–10 cm, 10–20 cm, 20–30 cm, 30–40 cm and 40–50 cm). The results indicated that the splash erosion was distributed at a splash distance of 0– 20 cm for the Lou soil and the Drab soil. Under the same type of raindrop, the splash volume of the Drab soil was higher than that of the Lou soil. For the Lou and Drab soils, the relation between the amount of splash and raindrop size increased linearly ($r^2 = 0.985$ and 0.860, respectively, $p < 0.01$), and a highly significant exponential relationship was found between splash distance and raindrop size ($r^2 \geq 0.967$, $p < 0.01$). The amount of splash detachment increased with increasing raindrop size for the two soil types. The maximum splash erosion occurred when the raindrop diameter was 5.45 mm. Macro-aggregates >0.25 mm broke apart to form micro-aggregates of <0.25 mm. Models were developed to predict the amount of splash erosion (M) for a given raindrop size (D) and splash distance (S) as follows: $M = 0.741D^{4.846}S^{-1.820}$, $r^2 = 0.916$, $p < 0.01$ and $M = 2.104D^{4.450}S^{-2.135}$, $r^2 = 0.904$, $p < 0.01$. Thus, large amounts of micro-aggregate dispersion and breakdown result in soil surface sealing and soil pore clogging.

1. Introduction

Soil aggregate stability has been used to indicate both soil quality and the resistance of soil to erosive agents (Bronick and Lal, 2005; Nichols and Toro, 2011). Aggregate breakdown and soil dispersion, which are caused by raindrop impact and the equipment used for soil tillage, are the first key steps of soil erosion processes (Shainber et al., 1992; Legout et al., 2005b). These initial steps may affect soil porosity, resulting in decreased infiltration and hydraulic conductivity as well as increased surface sealing and susceptibility to erosion (Raine and So, 1993; Fuller, 1995; Jasinska et al., 2006; Huang et al., 2010; Falsone et al., 2012; Salles et al., 2000; Ramos et al., 2003; Li et al., 2008). In addition, soil aggregates physically protect organic matter (Gregorich et al., 1994; Feller and Beare, 1997; Li and Pang, 2014), which is important for carbon sequestration.

It is well known that the extent of soil aggregate damage depends on changes in rainfall duration. Several methods for measuring soil aggregate stability have been developed (Le Bissonnais, 1988, 1990; Le Bissonnais et al., 1989; Pierson and Mulla, 1989; Beare and Bruce, 1993; Loch and Foley, 1994; Ame'zketa et al., 1996). Studies have shown that changes in the mechanical breakdown indexes of soil aggregates are related to rainfall duration through a power function (Ma et al., 2014). Yang et al. (2012) found that the first 1.5 mm of rainfall was mainly responsible for aggregate breakdown when soils were subjected to simulated rainfall with an intensity of 60 mm h^{-1}. Multiple studies have been conducted regarding the effects of rainfall on slope erosion and the particle size distribution characteristics of soil fragments (Lado et al., 2004; Abu-Hamdeh et al., 2006; Furbish et al., 2007; Warrington et al., 2009; Yan et al., 2010). Soil aggregate size distribution and stability affect the distribution, connectivity, and morphological characteristics of soil pores (Biox-Fayos et al., 2001). Legout et al. (2005a) used simulated rainfall to analyze the effects of different particle size distributions on soil aggregate characteristics but did not analyze the differences between specific particle sizes. Ma et al. (2014) used the fractal dimension (D) and the enrichment ratio (ER) to

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Table 1
Characteristics of the soil at the study site (mean volume ± SD).

Soil type	BD (g cm^{-3})	OM (%)	TN (g kg^{-1})	TP (g kg^{-1})	pH	$CaCO_3$ (g kg^{-1})	CEC (cmol kg^{-1})	Sand (%)	Silt (%)	Clay (%)
Lou soil	1.37 ± 0.13	1.31 ± 0.04	1.04 ± 0.02	0.62 ± 0.02	8.21 ± 0.04	74.54 ± 31.28	18.06 ± 3.61	29.96 ± 6.64	43.68 ± 3.71	26.36 ± 3.97
Drab soil	1.29 ± 0.07	2.27 ± 0.02	0.87 ± 0.03	0.83 ± 0.05	7.66 ± 0.03	135.18 ± 31.81	18.85 ± 2.89	28.74 ± 5.26	47.08 ± 5.15	24.18 ± 3.81

calculate the aggregate size distribution of a red loam soil. This study demonstrated that the aggregates were easily dispersed at the beginning of rainfall and that the effects of splash erosion decreased as a power function of increasing particle size. However, most studies have only considered aggregate stability under wetting processes or simulated drop impact. Few studies have considered the effects of raindrop size and aggregate breakdown together during splash erosion. Although the methods presented by Le Bissonnais (1988, 1990), Le Bissonnais et al. (1989) and Ame'zketa et al. (1996) represent the forces responsible for the mechanical breakdown of aggregates, they do not consider the additional effects of raindrops on sealing.

The objectives of this research were to evaluate the relationships between raindrop size and soil aggregate breakdown by using simulated tests and to analyze changes in the splash detachment and transport of aggregate fragments when subjecting soils to rainfall with 6 different raindrop sizes and 5 different raindrop distance intervals.

2. Materials and methods

2.1. Study site and soil samples

The study sites are located at Yangling (108°03′30″E, 34°18′25″N) and Meixian (107°45′36″E, 34°17′24″N) within the Shanxi Province in the southern Loess Plateau, which is a traditional agricultural planting region in China. These regions have a warm, sub-humid continental climate; in Yangling and Meixian, the average annual temperature is 13.0 °C and 12.9 °C, respectively, and the average annual precipitation is 660 mm and 610 mm, respectively, that mainly occurs in July, August and September. Soil erosion within these areas is severe. The studied soils are Lou soil and Drab soil, which form from loess parent material and are relatively deep soils with loam and silt-loam textures (classified within the Ustalf soil order according to USDA particle size classification criteria). The major crops grown in this region include maize (*Zea mays* L.) and winter wheat (*Triticum aestivum* Linn). Sixty samples were collected from the top layer (0–5 cm) of cultivated land (mean slope of 4°–7°) using a cutting ring (diameter of 10 cm × height of 5 cm) and the diagonal method. The organic matter, total nitrogen content, total phosphorus content, bulk density and particle size distribution were analyzed using the traditional methods described in Table 1.

2.2. Test device

The artificial rainfall device used in this study consisted of two parts: a raindrop generator and a splashed raindrop-collecting device. (i) The raindrop generator was a cylindrical box with an open top (10 cm diameter, 10 cm height). In the floor of the box, 21 syringe needles (US needle sizes of 7, 9, 12, 14 and 16) were installed at intervals of 2 cm. A constant hydraulic head was kept in the box during the rainfall simulations. Raindrop size was controlled by changing the needle size and by adjusting the height of the hydraulic head in the box. (ii) The collecting device for the splashed raindrops consisted of a stainless steel pan with a diameter of a 110 cm containing six concentric circles composed of wire (Fig. 1). The center of the splash pan had a radius of 5 cm and was used to place the open cutting ring (diameter of 10 cm × height of 5 cm) vertically. The center of the splash pan was regarded as the center point, and the wire was placed at radii of 15 cm, 25 cm, 45 cm, 35 cm and 55 cm to create five rings with distances of 10 cm, 20 cm, 30 cm, 40 cm and 50 cm, respectively, from the first round edge. The drain holes under the bottles was diameter of 1 cm holes to collect splashed soils. The wire bound to the splash pan was impervious, and each concentric circle contained two symmetrical drains. The splashed fragments were collected for each of the five distances (0– 10 cm, 10– 20 cm, 20– 30 cm, 30– 40 cm, 40– 50 cm). Outside of the experimental device, a plastic film was placed to prevent the effects of horizontal airflow disturbance on the rainfall. A new test plot was prepared after each rainfall event.

Six raindrop sizes were used, with a rainfall duration of 10 min. Five replicates were performed for each raindrop diameter. The raindrop sizes and the main parameters of the simulated raindrops are shown in Table 2.

2.3. Sample analysis

At the end of each test, all of the splashed aggregate fragments resulting from the five different raindrop sizes and the five distance intervals were washed, collected from the drains using ethanol (Le Bissonnais and Arrouays, 1996) and sieved to separate the aggregates into size fractions of >2 mm, 1– 2 mm, 0.5– 1 mm, 0.25– 0.5 mm, 0.106– 0.25 mm, 0.053– 0.106 mm and <0. 053 mm according to an aggregate analyzer (HR-TTF-100, Shunlong Experiment Instrument Factory, Yuxi City, Zhejiang Province of China). All aggregate fragments were oven-dried for 24 h at 105 °C and weighed.

2.4. Data analysis

All data analyses, including correlation and regression analyses, were performed using the SPSS statistical software version 16.0 and Microsoft Office Excel 2003. Origin 8.5 was used to visualize the data.

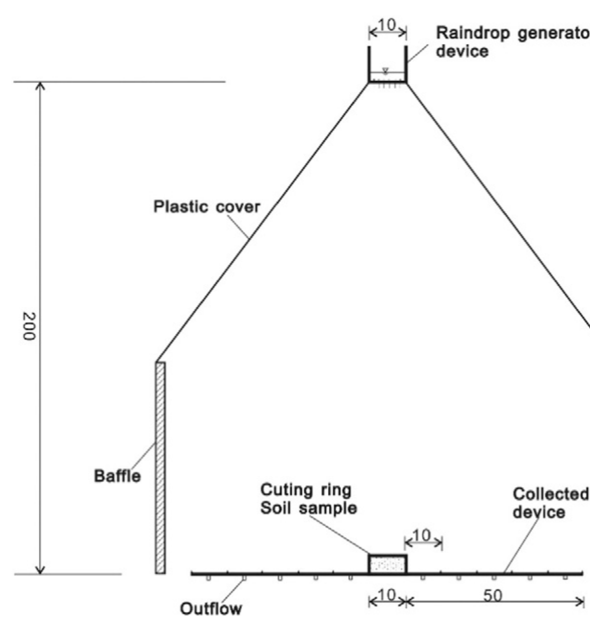

Fig. 1. The test for splashed raindrops and soil aggregates (unit: cm).