Catena 167 (2018) 411–421

Contents lists available at ScienceDirect

Catena

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

Effects of herbaceous vegetation coverage and rainfall intensity on splash characteristics in northern China

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ARTICLE INFO

Keywords:
Vegetation coverage
Rainfall intensity
Splash erosion
Splash distance
Size distribution

ABSTRACT

The splash erosion characteristics of the herbaceous-dominant area in northern China remain uncertain. A total of 21 plots (3-m wide × 3-m long) were installed to investigate splash characteristics under different vegetation coverages (0%, 5%, 10%, 20%, 40%, 60%, and 80%) and rainfall intensities (40, 80, and 120 mm/h) using an artificial simulated rainfall device and an improved splash tray. Splashed particles were collected and analyzed for mass and size distribution. This study demonstrated that a vegetation coverage of 40% would help protect soil from splash erosion. Total splash amount generally decreased exponentially with increasing vegetation coverage and splash distance, but rose with increasing rainfall intensity. Vegetation coverage played a more important role in the mass-weighted average splash distance, with a significant Pearson correlation of −0.934 ($p < 0.01$), compared to the rainfall intensity, with no significant correlation ($p > 0.05$). Moreover, splashed particles were finer than the original soil matrix because finer soil particles (clay, fine silt, and coarse silt) were transported preferentially by raindrops, and almost all mean weight diameters were lower than that of the soil matrix. Coarse silt showed the largest mass percentage at all splashed distances relative to the least mass percentage of coarse sand. The mass percentages of clay, fine silt, and coarse silt were generally positively correlated with vegetation coverage and splash distance and negatively correlated with rainfall intensity ($p < 0.05$). Furthermore, the opposite was true for fine and coarse sand ($p < 0.05$). These results could facilitate the further understanding of splash erosion characteristics and provide some suggestions for erosion control practices in northern China where herbaceous plants are important ingredients.

1. Introduction

Splash erosion, considered as the first step in the soil erosion process, has an important influence on the entire erosion process (Kinnell, 2005; Erpul et al., 2008; Mouzai and Bouhadef, 2011; Angulo-Martínez et al., 2012). It is a complex process of soil fragments detachment and transportation caused by raindrop impact (Morgan et al., 1998; Morgan, 2001; Legout et al., 2005a; Liu et al., 2016a). Splash erosion starts at the onset of a rain event and ends when raindrops stopped penetrating the runoff flow. Raindrops that hit the surface transfer a part of their kinetic energy onto the surface, thereby destroying aggregates and facilitating soil particle migration (Marzen et al., 2015). These conditions may affect soil porosity, which results in seal formation, reduces infiltration and hydraulic conductivity, and increases soil erosion (Loch and Foley, 1994; Salles and Poesen, 2000; Ramos et al., 2003; Wang and Chen, 2016; Fu et al., 2017).

Splash erosion depends on many factors including topography, soil properties, vegetation cover, and rainfall properties, such as raindrop size distribution, raindrop terminal velocity, raindrop shape, kinetic energy, and rainfall intensity (Ntahimpera et al., 1997; Ma et al., 2014a; Wang et al., 2014). Slope gradient has a complex influence on splash erosion relative to erodibility and erosivity (Bryan, 1979; Quansah, 1981; Mizugaki et al., 2010). Several studies have found that splash erosion can be accelerated by increased raindrop size and rainfall intensity (Quansah, 1981; Nanko et al., 2004) because they can influence rainfall kinetic energy by determining the mass and number of raindrops at a certain time. In addition, splash erosion is profoundly correlated with the land-surface evolution by plant-soil interactions (Wainwright et al., 2000; Furbish et al., 2009) because vegetation can influence splash erosion amount by causing raindrop redistribution under the vegetation cover (Staelens et al., 2006; Nanko et al., 2008; Ma et al., 2015).

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https://doi.org/10.1016/j.catena.2018.05.019
Received 30 August 2017; Received in revised form 12 May 2018; Accepted 17 May 2018
Available online 24 May 2018

Dunne et al. (2010) proposed a splash transport equation that relates the cover density, hillslope angles, and raindrop diameter by assimilating field and laboratory experiments. The equation reveals that splash mass decreases exponentially with the increase in cover density and increases rapidly as the median raindrop diameter expands. However, the applicability of the equation was limited because it was a very complex mechanistic model. Afshin et al. (2011a) studied splash and sheetwash erosions separately over a steep slope in a Japanese beech forest plot with different ground cover percentages. However, their studies failed to extensively discuss the effect of rainfall intensity on splash erosion under different herbaceous vegetation coverages, which is crucial to understanding the mechanism of vegetation function in erosion control.

The size distribution of splashed particles is essential for soil erosion and chemical transport models (Sutherland et al., 1996; Wan et al., 1996; Beguería et al., 2015). Furthermore, a significant amount of constructive results have been obtained by many scholars (Legout et al., 2005a; Malam Issa et al., 2006; Wang et al., 2014; Fu et al., 2017). Splashed particle distribution at different distances is important for understanding splash erosion process. Furbish et al. (2007) illustrated the raindrop-grain momentum transfer process and the relationship between the proportion of ejected grains and this process by using high-speed imaging. In addition, they theoretically partitioned the splash process upslope and downslope and characterized it with asymmetry in both quantity and distance. However, the effects of vegetation coverage and rainfall intensity on splashed particles, size distribution, and splash distance are rarely studied.

Many splashed particle collection devices, such as splash cups (Sreenivas et al., 1947; Kinnell, 1982), splash boards (Kwaad, 1977), and splash trays (Gabriels and Moldenhauer, 1978; Quansah, 1981; Wan et al., 1996) are often used to collect splashed materials from the surrounding area. These devices cannot accumulate all splashed soil particles, and thus the amount of collected soil particles is not equal to the actual detached mass (Rose, 1960; van Dijk et al., 2002). Therefore, experiments on the effects of vegetation and rainfall intensity on splash size selectivity and splash distance should be conducted using improved devices.

Soil and water erosion problem is serious in Northern China because of thin soil depth and > 50% of rainfall concentrated from June to August, restricting the development of agriculture and forestry and leading to continuous deterioration of ecological environment (Cheng et al., 2015). It can be significantly prevented by herbaceous vegetation filters which could effectively improve soil physical and chemical properties and ecological environment (Meyer et al., 1995; Zanders, 2005; Pan et al., 2010; Wang and Chen, 2017). As the first step in the soil erosion process and one of the main soil erosion forms in northern China, the effects of vegetation coverage and rainfall intensity on splash erosion should be determined to control erosion. Thus, this study aims to (1) determine the amount of splashed particles and its distribution with splash distance and (2) characterize the size distributions of soil particles under different vegetation coverages and rainfall intensities using improved splash trays.

2. Materials and methods

2.1. Field site and plot selection description

The field site is in the Shangxin County in Yanqing Town of Beijing, China. The area has geographical coordinates of 116°03′11″–116°04′19″ E and 40°26′19″–40°27′26″ N with an altitude of 700 m above the mean sea level (Fig. 1). This area is characterized by a continental monsoon climate with an average annual temperature of 8.5 °C. The mean annual precipitation is 474.5 mm, which is mainly concentrated from June to August with > 50%. The soil was classified as Alfisols according to the USDA Soil Taxonomy classification.

The maximum diameter of the improved splash tray used in this study was 2.2 m. In order to accommodate its size, a total of 21 3 m × 3 m plots with the same kind of soil were selected at a slope of 5%. The slope was set according to the topography characteristics of the study area. These plots were exposed under natural rainfall for five months since the middle of January to simulate natural field conditions. Soil characteristics were then tested as reported in Table 1. Particle size was determined by an EyeTech Particle Size and Shape Analyzer (AZ-S0300, Ankersmid Corporation, Netherlands). Organic matter content was analyzed by dichromate acid digestion (Walkley and Black, 1934). As shown in Table 2, soil aggregate stability was also measured by stirring treatment (Legout et al., 2005b).

Six different vegetation coverages of 0%, 20%, 40%, 60%, 80% and 100% were designed to investigate the effects of herbaceous vegetation cover on soil erosion process in the same study area (Fan, 2014). In order to fully study the effects of herbaceous vegetation cover on splash erosion, more coverages of 5% and 10% were added in this study. Moreover, the maximum coverage value was 80% because vegetation coverage of 100% was difficult to achieve under natural condition. Therefore, the 21 planted plots were divided in 7 vegetation coverage classes, 0%, 5%, 10%, 20%, 40%, 60%, and 80%, with a replication of 3 plots. Five months after the exposure, *Pennisetum alopecuroides* L., *Lolium perenne* L., and *Festuca ovina* L were planted in these plots. The vegetation coverage was controlled by trimming the leaves and determined by analyzing the photographed picture of vegetated plots.

2.2. Experiment design

Rainfall experiments were conducted after vegetation were planted for approximately 2 months, with a stem height of 6–8 cm (Fig. 2). The artificial simulated rainfall device (QYJY-501, Xi'an Qingyuan Measurement and Control Technology Corporation, China) with a spray system was employed in this experiment. The device covered a 4 m^2 horizontal rainfall area. A sprinkler system comprising of four groups of nozzles was located at the corner of a 2 m × 2 m rectangular frame. Each group included three nozzles, which were supplied by a water tank through a water supply system controlled by a pressure adjuster. Raindrop fall height was 4.0 m, and the raindrop median diameter ranged from 1.7 mm to 2.8 mm. Rainfall intensity was adjustable and ranged from 20 mm/h to 150 mm/h.

An improved splash tray was used to measure captured soil particles at different distances (Fig. 2). The inner circular area (splash source), with a diameter of 100 cm, at the center of the splash tray was the experimental plot that underwent the simulated rainfall. Although some relative heavier particles, detached in the center, might not reach the tray at all, the scale of the improved splash tray is reasonable according to Stroosnijder (2005) who stated that relevant spatial scale of splash erosion research at agricultural scales was about 1 m^2. In natural splash erosion, these heavier particles could be detached many times before being transported to further distance. In addition, the circular splash tray improves the uniformity of splashed particles collection. Moreover, the runoff generated during rainfall experiments was discharged through the space between soil surface and splash tray, avoiding the occurrence of surface runoff under higher rainfall intensity which can affect the results of the splash experiment. Each quadrant splash tray included 12 5-cm wide intervals and was marked with a direction (up, down, left, or right). The soil particles that splashed from the inner circular area were collected by quadrant splash trays. A plastic shed was used over the splash trays to avoid possible secondary splash erosion during rainfall period. Almost no splashed particle was found on the plastic shed, indicating no splashed particle outside the tray. Therefore the scale of the splash tray was appropriate in this study.

Only a minimal effect on splash erosion was observed when the rainfall intensity was < 20 mm/h, and obvious increases of splash amount were found in the study area under vegetation coverage of 0% (Cheng et al., 2015). Therefore, three rainfall intensities (i.e., 40 ± 1.14 mm/h, 80 ± 2.35 mm/h, and 120 ± 4.26 mm/h) were