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Rainfall intensity and slope gradient effects on sediment losses and splash from a saline–sodic soil under coastal reclamation

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ABSTRACT

Rainfall intensity and slope gradient play important roles in soil erosion processes. This study was conducted to investigate the effects of rainfall intensity and slope gradient, as well as of their interactions, on splash and overland flow transport on saline–sodic soil slopes. Rainfall intensities of 85, 95, 110 and 125 mm h^{-1} were applied to slope gradients of 6°, 11°, 22° and 35°. Splash was partitioned into four directional components. Runoff, sediment and splash samples were collected throughout the rainstorms and infiltration was calculated. The final infiltrations under the lower rainfall intensities of 85 mm h^{-1} were the largest for every slope gradient, but they decreased by 39.3% as the slope gradient increased from 6° to 35°. However, the final infiltration rates exhibited an increasing–decreasing trend for rainfall intensities higher than 85 mm h^{-1} as the slope gradient increased. The critical slope gradient was about 11°. The influence of rainfall intensity on runoff was considerably reduced at the higher slope gradients due to increased infiltration. The influence of slope gradient on sediment loss was reduced as rainfall intensity increased, while the effect of rainfall intensity on sediment losses was greater on the gentler slopes than on the steeper slopes. The upslope splash (mean value) initially increased from 4.8 to 7.2 g m^{-1} h^{-1} before it decreased to 3 g m^{-1} h^{-1} as the slope gradient increased. The maximum measured value occurred when the slope gradient was 22°. Total splash increased to maximum levels as the slope gradient increased to 11°, but decreased with further increases in gradient. These results indicated that the effects of slope gradient and rainfall intensity on sediment losses, runoff and splash were interconnected.

1. Introduction

Soil erosion by rainfall is a serious ongoing worldwide environmental issue that contributes to soil and water quality degradation. The erosion process can be divided into two sub-processes: i.e., splash and overland flow dynamics (Fu et al., 2011). Splash involves the detachment and transport of soil material by raindrop impact. The overland flow dynamics involve the transport of sediment, which comprises the detached soil particles from either raindrop impact or overland flow shear forces, either in sheet or rill flow (Luk and Merz, 1992; Kinnell, 2005). Knowledge of these processes is essential in appreciating the extent and causes of soil erosion, and in planning soil and water conservation measures (Hashim et al., 1995; Mermut et al., 1997; Defersha and Melesse, 2012).

Various factors, which include rainfall, topography, soil properties, vegetation and land management, greatly influence the soil erosion processes (Kim and Miller, 1996; Fox et al., 1997; Gabriels, 1999; Fox and Bryan, 2000; Assouline and Ben-Hur, 2006; Defersha and Melesse, 2012; El Kateb et al., 2013). A vast number of studies have investigated the many aspects of soil erosion. Many have investigated the effect of rainfall intensity and/or slope gradient on the dynamics of the erosion process. Fox et al. (1997) and Fox and Bryan (2000) indicated that the dominant influences of slope gradient on infiltration rate resulted from the changes in overland flow depth and surface storage. Assouline and Ben-Hur (2006) found that the influence of slope gradient on infiltration increased with rainfall intensity when seal formation interacted with interrill erosion. Defersha and Melesse (2012), investigating three soils (Eastern Ethiopia Alemaya Black soil, Regosols and Cambisols) that had textures ranging from clay to sandy clay loam, found that the effects of slope and rainfall intensity on sediment concentration and sediment yield varied with soil type and antecedent soil moisture content. El Kateb et al. (2013) determined the degree of soil erosion and surface runoff from different slope gradients under various vegetation covers. These studies all indicated that the degree of soil erosion was related to rainfall intensity and slope gradient.

Under raindrop impact, the physical properties of a soil surface change significantly. Variations in infiltration rate, soil water content, water suction, bulk density and surface roughness are all affected by raindrop impact (Fohrer et al., 1999), and this is mainly due to the formation of a surface seal that is primarily created by raindrop impacts (Assouline, 2004; Bradford et al., 1987; Mualem et al., 1993). Many

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studies have investigated the effects of surface seal induced variations on infiltration, runoff and erosion processes (Bradford et al., 1987; Mualem et al., 1993; Foley and Silburn, 2002; Assouline, 2004). Norton (1987) examined the micro-morphology of surface seals developed under simulated rainfall. He concluded that differences in infiltration rate, splash detachment or near-surface shear strength could not be explained well by the total porosity of the soil surface seal, but that final infiltration was better related to the percentage of planar pores or cracks. The soil surface is also affected by the runoff. Sharpley (1985) found that the EDI (Effective Depth of Interaction between the surface soil and runoff) increased (1.30–37.43 mm) with an increase in rainfall intensity (50–160 mm h^{-1}) and soil slope (2%–20%), although the magnitude differed according to the soil. The effect of rainfall intensity was attributed to the increased runoff energy, which enhanced the mixing of the surface soil with the water layer. Therefore, these different studies indicated that the increasing rainfall intensity both indirectly and directly affected the soil surface conditions, the infiltration rate and the runoff, which are both related to the erosion process.

Slope gradient is one of the major factors affecting soil particle detachment and transport (Fu et al., 2011). Slope gradient is also related to several critical factors affecting the infiltration rate; these factors include surface sealing, water surface storage, effective rainfall intensity and overland flow depth (Poesen, 1984; Fox et al., 1997). To some extent, slope gradients may have direct impacts on runoff erosivity, percolation and soil erodibility, and thus indirectly affect the development of rills (Li et al., 2010).

Saline–sodic soils such as those under consideration in this study have the distinctive characteristic of containing excessive concentrations of both soluble salts and exchangeable sodium (Richards, 1954). The electrical conductivity of their saturation extracts is often greater than 4 mS cm^{-1} and the exchangeable-sodium percentage is greater than 15. For saline–sodic soils, the relatively high salinity in the soil solution has a flocculating effect on the soils, pushing adsorbed cations closer to the soil particle surfaces and increasing the cohesion within and among soil aggregates. Such soils will remain more permeable (Western Fertilizer Handbook, 1995). High sodium concentrations have an effect on soil dispersion. Dispersion of clay particles in soils causes plugging of soil pores, which contributes to reductions in infiltration and hydraulic conductivity and to increases in surface sealing (Quirk and Schofield, 1955; Rengasamy et al., 1984; Warrence et al., 2002).

Tidal flats are often reclaimed so that the new land and its resources may be exploited, and the opposing effects of clay dispersion and flocculation play a significant role that impacts coastal development strategies. For example, in Jiangsu Province, China, during the reclamation of tidal flats on the shores of the Yellow Sea, a supporting network of water channels is constructed in order to both conserve and drain water resources. The construction generates many exposed excavated slopes such as those of the banks of ditches, drainage channels, streams and rivers. Given the region's abundant rainfall and the high soil sodium salinity, these slopes are highly erodible and unstable, which potentially leads to their collapse. The conditions for erosion from these slopes differ to some extent from those on other types of soil slope (She et al., 2014a). Thus, more information is needed in order to understand the erosion processes that occur on these slopes that are related to splash and overland flow transport under different conditions of rainfall intensity and slope gradient. However, few studies have investigated saline–sodic soil slopes. In order to address this need, the objectives of this study were as follows: (1) to quantify the independent effects of slope gradient and rainfall intensity on splash and overland flow transport on saline–sodic soil slopes; (2) to determine the interactive effect of rainfall intensity and slope gradient on erosion from saline–sodic soil slopes; and (3) to discuss the influence of the sodium ion concentrations on the erosion processes.

2. Materials and methods

2.1. Soil material

The soils used in this study were collected from Rudong County, Nantong City (120°42′ to 121°22′ E and 32°12′ to 32°36′ N), Jiangsu Province, China (Fig. 1A). This low-lying flat area is located beside the Yellow Sea and the altitude only ranges between 3.5 and 4.5 m above mean sea level. It is dominated by a subtropical moist monsoon climate having a mean annual rainfall of 1026 mm, 68% of which falls between May and September (She et al., 2014a). The mean daily temperature is 14.8 °C, and the annual potential evapotranspiration is 1343.5 mm.

The predominant soil in this reclamation region is a sullage–puddle soil (Zhang et al., 2013). Due to the high sodium content, the soil structure is poor. Disturbed soil samples were collected from the top 100 cm of a farmland area (Dongling Farm), which was reclaimed in 2007 (Fig. 1B). The clay, silt and sand components of the soil samples were 8.5%, 52.9%, and 38.6%, respectively. The soil organic matter content was 3.26 g kg^{-1}, the sodium (Na) ion content was 1.60 g kg^{-1}, the exchangeable sodium percentage (ESP) was 68.9%, and the soil electrical conductivity (EC) of a 1:5 soil to water extract was 5.98 mS cm^{-1}. More details about the methodology by which the ESP and EC were determined can be found in She et al. (2014b). The sampled soils were air dried, passed through a 4-mm sieve, and thoroughly mixed.

2.2. Experimental setup

Rainfall events were simulated by a Lateral Jet Rainfall Device. This device produces rainfall with a fall height of 6 m and, by adjusting pressure gauges, at the intended rainfall intensity. Since heavy rainfall storms occur frequently in the region and heavy rainstorms (>50 mm h^{-1}) frequently cause the most severe soil erosion, four high rainfall intensities (85, 95, 110 and 125 mm h^{-1}) were simulated in this study. The rainfall duration was 80 min, which was sufficient to produce enough runoff data to meet the study objectives. Rainwater was simulated by using deionized water.

A tray with dimensions of 50 cm × 30 cm × 15 cm (length × width × height) packed with soil was subjected to the simulated rainfall. Relatively small trays such as these, or even smaller ones, have been used in many other studies (e.g., Assouline and Ben-Hur, 2006; Warrington et al., 1989; Mamedov et al., 2001). While not exactly replicating field conditions, they suffice to gain insights into the changes in interrill erosion processes occurring under controlled conditions and, as such, play an important role in gaining an understanding of soil erosion processes. The trays were set on a framework that could be inclined to give different slope gradients (Fig. 2). Four slope gradients (6°, 11°, 22° and 35°) were evaluated in this study based in part on the range of slopes found in the reclamation project in Rudong County.

Four metal sidewalls with collection troughs were attached to the trays in order to collect the splashed material separately from the sediment loss in the runoff (Fig. 2). The four sidewalls collected all of the splashed material projected over the tray sides at a height of 20 cm or less above the soil surface. Runoff containing sediments was collected via an 8-mm wide trough installed at the downslope edge of the soil tray; the trough was covered during rainstorms to prevent rainwater from mixing with the collected runoff.

Trays were packed prior to a rainfall simulation experiment. Layers of gravel, cotton and soil were packed sequentially. A layer of gravel (4.5 cm thick) was placed in the soil tray. This layer was then covered with a layer of cotton (0.5 cm thick), which prevented soil materials from entering the gravel layer but allowed the free drainage of water and permitted air to escape. Two soil layers, each 5 cm thick, were then packed into the tray to a bulk density of 1.3 g cm^{-3}. To ensure that there was continuity between the two soil layers, the surface of the lower layer was raked before packing the upper layer. The packed trays were then positioned under the rainfall simulator, adjusted to