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Influence of cohesive and disruptive forces on strength and erodibility of tropical soils

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ABSTRACT

Direct impact of intense tropical rainfall following deforestation and other deleterious land practices is one of the major causes of land degradation in the Caribbean. The susceptibility of the exposed soil to degradation depends on the cohesive strength of soil binding factors and the magnitude of disruptive forces produced by the intense rainfall. We propose that the combination of cohesive binding factors of clay and organic matter in a soil subjected to varying wetting conditions exert a strong influence on the resistance of the soil to sustained shearing stresses. Simulated rainfall experiments involving intense rainfall of 120 mm h^{-1} were conducted on six Trinidad soils selected based on three levels of clay and two levels of organic matter. Samples were either left dry or pre-wetted with mist at slow (7.5 mm h^{-1}) and fast (75 mm h^{-1}) wetting rate to antecedent water content of 0.5 of field capacity and field capacity, followed by exposure to the intense simulated rainfall. We found that increase in clay content did not necessarily increase the cohesive strength of low organic matter soils since high clay soils shear and crust as much as low clay soils under the shearing stresses of intense rainfall and fast wetting. At high organic matter content, however, the resistance to shearing stresses increased at medium and high clay contents suggesting that high organic matter is required at these clay contents to reduce the surface tension of water entering the clay–organic matter matrix and thus increasing the cohesion of the clay particles. For medium to heavy textured soils of the humid tropics subjected to disruptive forces of intense rainfall, interaction rather than the individual effects of clay and organic matter control their erodibility.

1. Introduction

Water erosion is a major agricultural and environmental problem in the humid tropical Caribbean characterize by intense rainfall, hilly landscape and structurally weak soils. In the Republic of Trinidad and Tobago, studies have shown that >80% of the soils are highly susceptible to structural breakdown and prone to runoff and erosion (Ahmad and Roblin, 1971; Wuddivira et al., 2009a,b; Wuddivira et al., 2010). Soil loss to rivers and streams cause major agricultural and environmental problems in these twin Islands.

Splash detachment (SD) is an initial step in the erosion process (Cruse et al., 2000; van Dijk et al., 2002) and is a good measure of the resistance of the soil to erode when exposed to erosive forces. Rachman et al. (2003) studied the influence of long-term cropping systems on soil physical properties related to soil erodibility and concluded that SD was a more sensitive test than other physical measurements for evaluating changes in soil erodibility. Similar observations were made by Gantzer et al. (1987) and Bradford et al. (1986). Abu-Hamdeh et al. (2006) explained that the splash process involves lifting of grains from the aggregate against the resisting force of inter-aggregate cohesion and the weight of the aggregate. Soil erodibility is therefore influenced by many soil properties that affect the soil's resistance to erosive agents including, among others, texture (Bradford et al., 1987), aggregate stability (Grissinger, 1982; Coote et al., 1988), organic matter content (Tisdall and Oades, 1982; Haynes, 1993), clay mineralogy (Ruiz-Vera and Wu, 2006), exchangeable cations (Emerson, 1967), soil water condition (Cruse and Larson, 1977; Nachtergaele and Poesen, 2002) and shear strength (Rachman et al., 2003; Knapen et al., 2007).

Shear strength is one of the key mechanical properties influencing the tilth, water movement, plant growth, biological activity and erodibility of the soil (Blanco-Canqui et al., 2005; Eudoxie et al., 2012). It is the maximum resistance the soil material can sustain to shearing stresses. This is related directly to the cohesive forces between soil particles (Horn et al., 1994; Knapen et al., 2007) and therefore related to the aggregate stability of the soil (Horn et al., 1994) which is influenced by soil intrinsic

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properties such as clay and organic matter. The effect of texture on soil strength is either through frictional forces attributed to soils consisting of coarse particles or cohesive forces attributed to fine-textured soils. The soil organic matter concentration influences shear strength dynamics by modifying the cohesiveness of soil particles and structural stability (Blanco-Canqui et al., 2005). The effects of soil organic matter on shear strength are somewhat inconsistent. Some workers (e.g., Ohu et al., 1986; Blanco-Canqui et al., 2005) have reported a decrease in shear strength with increased soil organic matter concentration. They attributed this to the ability of organic matter to decrease bulk density (Kay et al., 1997; Kay and Angers, 1999), and a reduction in bulk density implies a reduction in soil strength. Conversely, however, soil organic matter increases cohesive force between soil particles which is directly related to soil shear strength (To and Kay, 2005). Therefore, many workers (Davies, 1985; Gantzer et al., 1987; Ekwue, 1990; Cruse et al., 2000; Rachman et al., 2003) found an increase in shear strength with increased soil organic matter concentration. Rachman et al. (2003) reported that soil shear strength increased as aggregate stability and soil organic matter content increased. Hence, soil management and cropping systems that accumulate organic matter which, in turn, reduce the soil's vulnerability to slaking and dispersion on wetting, increase the soil's resistance to penetration by the drop cone equipment, which is commonly used to assess soil strength (Ekwue, 1990; Rachman et al., 2003).

The maximum resistance the soil material can sustain to shearing stresses and hence to erosion is offered by bonding forces in the soil matrix (Horn et al., 1994). These bonding forces have also been shown to be influenced by conditions prevailing in the soil, such as antecedent water content (AWC) and the rate at which aggregates are being wetted. Mamedov et al. (2006) observed that at no aging (0.01 d), soil loss increased with an increase in AWC mainly because of enhanced slaking. Wuddivira et al. (2009a) demonstrated that the combined effect of slaking caused by fast pre-wetting and the ability of high water content to keep soil particles far apart reduces the opportunities of cohesion to develop and this reduces shear strength, which rendered the soils more erodible on exposure to intense rainfall. Despite the extensive studies on the effects of the time-dependent factors of AWC and wetting rate (WR) on soil erosion, however, findings are generally inconclusive with studies showing opposite effects. High AWC has been shown to increase soil loss on the one hand (e.g., Luk, 1985; Froese et al., 1999; Wangemann et al., 2000) and decrease them on the other (e.g., Le Bissonnais and Singer, 1992; Lado et al., 2004).

Soil wetting reduces soil shear strength (Cruse and Larson, 1977), which means the soil detachment rate may change during the actual rainfall event (Schultz et al., 1985). However, the studies of Al-Durrah and Bradford (1981), Nearing and Bradford (1985), Ekwue (1990), and Rachman et al. (2003) that used the fall cone method to determine surface shear strength and relate it to soil detachment except for Ekwue (1990), considered single-drop effect ignoring soil wetting effects that occur in a continuous rainfall. Texture and organic matter are key factors in the resistance of soils to erosive forces (Line and Meyer, 1989; Knapen et al., 2007) but the study of Ekwue (1990) only considered light textured soils (clay% <200 g kg^{-1}). The mechanisms involved in the way shear strength influences soil erodibility under rainfall will be better understood using soils of varying textural categorization. We propose that the combination of clay and organic matter in a sample subjected to varying wetting conditions exerts a strong influence on the resistance of the soil to sustained shearing stresses, to crust and to erode under intense rainfall of the humid tropics. The objectives of this study were (i) to quantify the combined effects of WR and AWC on the resistance of soils of varying levels of clay and organic matter to sustained shearing stresses and to crust under continuous intense simulated rainfall events typical of the humid tropics and (ii) to investigate the relationship between shear and crust strength with SD and aggregate breakdown (AB) of soils of varying levels of clay and organic matter subjected to different wetting conditions and exposed to intense rainfall.

2. Materials and methods

2.1. Site description and soils

Six soil-series, agriculturally important for shear strength, crust strength and splash detachment measurement were selected in Trinidad (10°3′N 60°55′W and 10°50′N 61°55′W), which is the southernmost of the Islands of the Lesser Antilles in the Caribbean Sea. Trinidad is located ~11 km from the NE coast of Venezuela near the out flow of the Orinoco River. The Island is characterized by a humid tropical climate, with mean annual maximum and minimum temperatures of 32 °C and 23 °C respectively and has a wet and dry season and a noticeable rainfall gradient from ~2500 mm yr^{-1} in the east to ~1500 mm yr^{-1} in the west (Beard, 1946; Granger, 1983). The rainfall occurs with high intensities of up to 250 mm h^{-1}. The wet season is from May to December which is often interrupted by a short dry spell, referred to as the *petit carême* (Gumbs, 1982). The six soils with predominantly kaolitic clay mineralogy (Table 1), were selected to provide a combination of three concentrations of clay (low, <200 g kg^{-1}; medium, 200–450 g kg^{-1}; and high, >450 g kg^{-1}) and two concentrations of organic matter (low, ≤30 g kg^{-1} and high, >30 g kg^{-1}). Other factors of aggregation such as exchangeable sodium percentage (ESP) and sesquioxides were not considered in the selection process due to their generally low content in Trinidad soils (Ahmad and Roblin, 1971; Wuddivira and Camps-Roach, 2007).

In this paper, we adopted the designation used by Wuddivira et al. (2009a) for the six soils as LcLom, LcHom, McLom, McHom, HcLom and HcHom for low clay low organic matter, low clay high organic matter, medium clay low organic matter, medium clay high organic matter, high clay low organic matter and high clay high organic matter respectively in accordance with the clay-OM level contained in a sample.

Soil samples were taken from the top 0–10 cm of the six soil series from undisturbed sites. Vegetation that have been on these sites for over 50 years included tree crops with tall grasses as understory in some sites and abandoned sugar cane and rice farms overtaken by tall grasses in others. Vegetation type on each of the six soils is presented in Table 1. Selected physical and chemical properties of the soils (Table 1) were determined using standard analytical methods (Klute, 1986; Page et al., 1986) which have been reported elsewhere (Wuddivira et al., 2009a). Water stable aggregates as an index of aggregate stability were assessed by the method described by Wuddivira et al. (2009b).

2.2. Splash detachment and aggregate breakdown studies

The procedure for the determination of SD and AB as influenced by AWC and WR for the six soils with varying clay and organic matter levels as used in this study is described in Wuddivira et al. (2009a). Briefly, a rainfall of 120 mm h^{-1} was produced by a continuous spray full jet nozzle (12.7 mm in diameter) attached to a Guelph Rainfall Simulator II (Tossell et al., 1990). Columns 7.3 cm in diameter and 5 cm high were uniformly packed up to their heights with known predetermined masses of air-dried soil aggregates <5 mm. The sieve size minimized the disruption of aggregates caused by sieving (Diaz-Zorita et al., 2002). The packing