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Misrepresentation of hydro-erosional processes in rainfall simulations using disturbed soil samples

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ABSTRACT

Interrill erosion is a primary soil erosion process which consists of soil detachment by raindrop impact and particle transport by shallow flow. Interill erosion affects other soil erosion sub-processes, e.g., water infiltration, sealing, crusting, and rill initiation. Interrill erosion has been widely studied in laboratories, and the use of a sieved soil, i.e., disturbed soil, has become a standard method in laboratory experiments. The aims of our study are to evaluate the hydro-erosional response of undisturbed and disturbed soils in a laboratory experiment, and to quantify the extent to which hydraulic variables change during a rainstorm. We used a splash pan of 0.3 m width, 0.45 m length, and 0.1 m depth. A rainfall simulation of 58 mm h^{-1} lasting for 30 min was conducted on seven replicates of undisturbed and disturbed soils. During the experiment, several hydro-physical parameters were measured, including splashed sediment, mean particle size, runoff, water infiltration, and soil moisture. We conclude that use of disturbed soil samples results in overestimation of interrill processes. Of the nine assessed parameters, four displayed greater responses in the undisturbed soil: infiltration, topsoil shear strength, mean particle size of eroded particles, and soil moisture. In the disturbed soil, five assessed parameters displayed greater responses: wash sediment, final runoff coefficient, runoff, splash, and sediment yield. Therefore, contextual soil properties are most suitable for understanding soil erosion, as well as for defining soil erodibility.

1. Introduction

Soil, as a major component of the ecosystem, has been facing major challenges. Soil is essential for food production and environmental services, but climate change and population growth impose great pressure on soil, increasing its degradation including soil erosion (Montgomery, 2007; Editorial, 2010; Norvig et al., 2010). Soil erosion is one of the most important modes of land degradation worldwide. Important advances in the study of soil erosion have occurred in terms of the methodology, knowledge of processes, and modeling (Ellison, 1950; Emmett, 1970; Govers, 1992; Morgan, 2005; Boix-Fayos et al., 2006; Govers et al., 2007; Knapen et al., 2007; Grismer, 2012; Zhang et al., 2014). In spite of this progress, many research gaps still exist, such as lack of a reliable soil erodibility concept and information on the temporal variation of the soil erodibility coefficient. New methodologies to explore different soil erosion sub-processes and soil erosion data from diverse locations must be provided (Wang et al., 2013), including those for agricultural disturbed soil. However, there is a deficiency in soil erosion studies, particularly in relation to hydrology and geomorphological processes (Bryan, 2000).

Interrill erosion, the detachment of soil particles by raindrop impact and their transport by shallow surface flow, has been widely studied via laboratory experiments (Moldenhauer and Long, 1964; Bryan, 1979; Bradford et al., 1987; Bradford and Foster, 1996; Fox and Bryan, 2000; Zhang et al., 2014). Laboratory experimentation has become standard method for research on hillslope processes in geomorphology, despite its limitations; for example, the materials used and processes observed in laboratory experiments may be different from those measured in the field (Bennett et al., 2015).

The use of a sieved soil, i.e., disturbed soil in interrill research is almost standard in laboratory experiments (Mutchler et al., 1994; Agassi and Bradford, 1999). This methodology to study interrill soil erosion has received criticism, since the natural soil architecture is essential to understanding the numerous biogeophysical processes, including rainfall–runoff processes. Therefore, to understand soil hydro-physical processes, experiments on an intact undisturbed soil should be preferred (Lin et al., 2006). However, few studies have been conducted using undisturbed soil samples. Research on the mechanism of soil detachment by overland flow comparing disturbed and undisturbed soils indicate that soil detachment rates are 1 to 23 times greater for

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disturbed soils than for natural undisturbed soils (Zhang et al., 2003). They used small soil core samples with 10 cm diameter. Whereas Shi et al. (2010) evaluated the aggregate breakdown mechanisms in interrill erosion processes, and found a close relationship between the mechanism and erosion rates in both disturbed and undisturbed samples. However, the undisturbed soil was measured in the field, and the disturbed soil was measured in a laboratory.

Therefore, it is necessary to conduct more studies using undisturbed soil samples in order to understand the interrill process and to evaluate the influence of hydraulic parameters on detachment rates. In addition, it is necessary to quantify how the many hydraulic variables involved in interrill processes change during a rainstorm over undisturbed and disturbed soils.

The aims of this study are to evaluate the hydro-erosional response of undisturbed and disturbed soils in laboratory experiments, to quantify the extent to which hydraulic variables change during a rainstorm and to discuss the contextual soil erodibility controlling factors. Establishing a model for soil erodibility and interrill erosion was not a primary objective of our study this time.

2. Material and methods

2.1. Soil characteristics and collection of undisturbed and disturbed samples

This study was developed for clay-textured Brown Oxisols according to the USDA soil taxonomy (USDA, 1998). The data on granulometry, chemical properties, organic carbon content, and grain size are shown in Table 1. The soil was collected in pair randomly (i.e., undisturbed plus disturbed sample) from an area (~1 ha) forested with *Pinus* spp. with slope of ~6–12%. The undisturbed sample was collected using an iron frame with the same dimensions as the splash pan, 30 cm wide, 45 cm long, and 10 cm deep. The iron frame with cutting edges was inserted into the soil, then the soil was extracted, and excess soil was removed from the sample. The soil sample bottom was cut with a steel wire. Then, in the field, the bulk soil was transferred carefully to a splash pan and prepared for rainfall simulation. The disturbed sample was collected from a site adjacent to the undisturbed sample site i.e., side by side. A shovel was used to excavate the soil to a depth of 10 cm. The soil was transferred gradually to the splash pan, forming layers that were gently crushed and compacted. And the larger roots and clods over 20 mm was removed from the splash pan (Agassi and Bradford, 1999).

The sample characteristics are summarized in Table 2. We attempted to reproduce the bulk density of the undisturbed soil in the disturbed samples (Table 2). The soil moisture content was measured before the rainfall simulation using a set of moisture sensors ($n = 7$), and was taken into account in the soil bulk density estimation. The soil bulk density was 5% greater in the undisturbed sample compared to the disturbed soil samples ($p > 0.05$). The rainfall simulation was performed on two consecutive days. (See Table 3.)

Table 1
Soil A horizon characteristics.

Soil characteristics (0–10 cm)	
Sand (%)	16.0
Silt (%)	28.0
Clay (%)	56.0
Bulk density (0–5 cm) (g cm^{-3})	0.85 ± 0.05
Topsoil shear strength (kPa)	33.2 ± 5.9
Mean particle diameter (mm)	2.96 ± 0.18
Soil organic matter (Walkley-Black) (g dm^{-3})	42.9
pH ($CaCl_2$ 0.01 M)	4.3
P (Mehlich) (mg dm^{-3})	1.6
Base saturation (%)	36.3
Cation Exchange Capacity (cmol dm^{-3})	13.45

Table 2
Sample characteristics soil weight and estimated soil bulk density.

Splash Pan	[1]Undisturbed soil sample weight (kg)	[2]Disturbed soil sample weight (kg)	Undisturbed soil bulk density (g cm^{-3})	Disturbed soil bulk density (g cm^{-3})
1	15.25	12.82	1.00	0.88
2	15.65	13.37	1.03	0.91
3	13.69	13.26	0.90	0.91
4	13.54	13.60	0.89	0.93
5	14.64	13.70	0.96	0.94
6	15.70	14.22	1.03	0.97
7	15.94	13.61	1.05	0.93
Average	14.86	13.63	0.98	0.93
Standard deviation	1.06	0.33	0.07	0.02
Coefficient of variation	7.2	2.5	7.2	2.5

Note: [1]Undisturbed sample soil moisture (0.161 ± 0.034 m^3 m^{-3}, $n = 7$); [2]Disturbed sample soil moisture (0.111 ± 0.017 m^3 m^{-3}, $n = 7$).

2.2. Experimental design

The multi-drop simulator consisted of a framework of pipes (20 mm diameter) and a 6-m-tall SPRACO cone jet nozzle, and water was supplied by an electric water pump with a pressure of 78 kPa. The simulated rainfall was dripped from a height of 6 m from the central plot for a period of 30 min with a rainfall intensity of 58.2 ± 7.3 mm h ($n = 10$). The drop diameter of the rainfall simulator varied from 0.35 to 6.35 mm, with a median drop size of 2.4 mm and a coefficient of uniformity over 90%. The device produced rain with 90% of the kinetic energy of natural rainfall, and with similar intensity (Luk et al., 1986).

The soil erosion apparatus was a central splash pan test area of 30 × 45 × 10 cm (width × length × depth) (Moldenhauer and Long, 1964). The splash pan is surrounded by a shield collector to measure the splash detachment (Bryan and De Ploey, 1983). In addition, the splash pan apparatus has a separate slot/trough to collect runoff and wash sediment, and a drainage outlet at the bottom to collect percolation (Fig. 1).

During the simulation, the soil erosion pans were tilted to a 9% slope. Also, during the experiment, the water temperature (18.2 °C ± 1.3 °C) and water electric conductivity (92.8 ± 4.9 μS) were measured four times. Runoff was collected for 1 min at regular intervals of 2 min (mm h^{-1} and %), and time to runoff (min) was measured when continuous flow was recorded at the trough. The total runoff and sediment yield i.e., total sediment splashed plus sheet wash sediment (kg m^{-2} h^{-1}) were calculated by integrating the 1-min runoff rates for the entire duration of the experiment. The entire percolation (i.e., infiltration – mm h^{-1}) was collected every 5 min. The total splash detachment (kg m^{-2} h^{-1}) composed by the material retained in the splash pan shield was collected at the end of the simulation. The sheet wash (kg m^{-2} h^{-1}) was collected for 1 min at regular intervals of 2 min.

Table 3
Summary of hydro-erosional variable changes compared for undisturbed and disturbed soil.

Parameter	Ratio Undisturbed/disturbed
Wash sediment (kg m^{-2} h^{-1})	−9.0
Infiltration (mm h^{-1})	+4.7
Final runoff coefficient (%)	−3.7
Runoff (mm h^{-1})	−2.8
Topsoil shear strength (kPa)	+2.4
Splash (kg m^{-2} h^{-1})	−2.1
Sediment yield (kg m^{-2} h^{-1})	−2.0
Mean particle size (mm)	+1.4
Soil moisture (m^3 m^{-3})	+1.3