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Dynamics of soil fragment size distribution under successive rainfalls and its implication to size-selective sediment transport and deposition

Pu Shi[a,*], Kristof Van Oost[b], Rainer Schulin[a]

[a] Institute of Terrestrial Ecosystems, ETH Zurich, Universitätstrasse 16, CH-8092 Zurich, Switzerland
[b] TECLIM - Georges Lemaître Centre for Earth and Climate Research, Université catholique de Louvain, BE-1348 Louvain-la-Neuve, Belgium

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ABSTRACT

Changes in soil fragment size distribution (FSD) under the impacts of successive rainfall events can have strong effects on sediment export during erosion events. However, field observations on the temporal dynamics of FSD under changing rainfall conditions are rare. In this study, we applied five successive artificial rainfall events with two different rainfall intensities (25.8 and 49.1 mm h^{-1}) on two replicated agricultural soil plots over a period of five weeks. Surface soil samples were taken immediately before and after each rainfall event and also in between the rainfall events in order to monitor surface aggregate stability and soil FSD. The FSDs resulting from rainfall-induced aggregate breakdown were used as inputs into a size-selective sediment transport model in order to assess how the variations in FSD would affect the concentration and size of exported sediments. Aggregate stability at first decreased due to generally wet conditions, but then increased with soil drying, until reaching a plateau towards the end of the experimental period. It did not fully recover to initial levels though, probably due to loss of stabilizing agents over time. Independent of soil moisture, notable re-aggregation occurred after each event but again did not reach the full restoration of the initial state even after up to 10 days of regeneration. In contrast to aggregate stability and irrespective of pre-event re-aggregation, the percentage of coarse fragments in post-event FSDs continued to decrease from event to event, suggesting that in addition to the previously re-formed aggregates also new coarse aggregates were broken down. The model simulations showed that the temporal variations in post-event FSD would have had as much influence on the amount and size distribution of sediments exported with surface runoff as a 3-fold variation in unit discharge, suggesting the importance of quantifying rainfall-induced FSD in soil erosion assessment.

1. Introduction

Soil aggregate stability has long been used as an indicator of soil erodibility and land degradation status (Barthes and Roose, 2002; Bird et al., 2007; Boix-Fayos et al., 2001; Le Bissonnais et al., 2007), and it is also directly used as model input to characterize soil resistance to erosion processes (Gumiere et al., 2009). Numerous studies have shown that aggregate stability changes over time in response to land management practices, climatic influences and soil conditions. Dimoyiannis (2009) found that aggregate stability showed seasonal changes, as it was (1) impaired by repetitive wetting from rainfall and freezing/thawing in winter, and (2) promoted by drying and warming due to enhanced microbial activity. Perfect et al. (1990) and Chan et al. (1994) reported decreased aggregate stability in winter and on conventionally tilled fields, noting also a negative effect of soil water content at the time of sampling. In the short term, Cosentino et al. (2006) observed substantial increase in aggregate stability one week after an amendment with crop residues, highlighting the important role of microbial decomposition. Conversely, Algayer et al. (2014) reported a decrease as high as 40% in aggregate stability over a few weeks without stimulation of biological activity. They concluded that soil water content, hydric history, and rainfall intensity were the controlling factors of surface aggregate stability.

Aggregate stability is a key factor in rainfall-induced aggregate breakdown processes (Le Bissonnais, 1996). Due to its influence on the size composition of the resulting fragments, it acts as a direct control on size-selective erosion processes (Leguedois and Le Bissonnais, 2004; Sajjadi and Mahmoodabadi, 2015; Wang and Shi, 2015). Legout et al. (2005) and Shi et al. (2017) demonstrated in laboratory and field experiments for a variety of soil conditions and rainfall parameters that aggregate breakdown follows a consistent two-stage pattern during heavy rainfall events, in which after an initial rapid breakdown stage

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Abbreviations: FSD, fragment size distribution; SWC, soil water content; SVD, settling velocity distribution; MWD, mean weight diameter; SSD, sediment size distribution

[*] Corresponding author at: CHN F28.2, Institute of Terrestrial Ecosystems, ETH Zurich, Universitätstrasse 16, CH-8092 Zurich, Switzerland.

E-mail address: pu.shi@usys.ethz.ch (P. Shi).

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Fig. 1. (a) Waterproof plastic cover protecting the surface of an experimental plot against natural rainfall and allowing ventilation during dry periods. (b) Experimental plot layout with sampling grid. S1 and S2 represent examples of randomly assigned grid cells from which replicate samples were taken at the first two out of 13 consecutive samplings.

the fragment size distribution (FSD) gradually converges to a quasi-steady state. The final FSD of the breakdown products can be considered as a proxy to represent the size distribution of the source materials that are available for size-selective sediment transport (Legout et al., 2005).

Aggregate stability and FSD also depend on previous rainfall impacts, as successive rainfalls of the same rainfall intensity and duration can result in vastly different erosion responses. Le Bissonnais and Singer (1992) applied three successive artificial rainfall events on the same plot over one week, and found general increases in both runoff and erosion rates with the development of surface crusts over time. Although initial aggregate stability was not quantified prior to each rainfall application, the results indicate that memory effects in soil surface condition from the preceding rainfall events played a key role in controlling soil erodibility. Also a number of other studies reported non-uniqueness of erosional responses from replicate plots or under the same rainfall/runoff conditions (Boix-Fayos et al., 2006; Kim and Ivanov, 2014; Nearing et al., 1999). Kim et al. (2016) attributed the source of this non-uniqueness partly to the variation in the size distribution of the particles available for transport and deposition, based on a numerical study. Using artificially generated particle size distribution data, they found that their multi-class sediment transport model based on the Hairsine-Rose theory (Hairsine and Rose, 1992) was highly sensitive to the size characteristics of the source materials.

The model developed by Hairsine et al. (2002) also used the same theoretical foundations to account for the size-selectivity of erosion processes across net deposition zones. In contrast to the conventional single-class erosion models (e.g. EUROSEM, WEPP and LISEM), this model divides the fragments resulting from aggregate breakdown, which is the source material that is available for transport and deposition, into an arbitrary number (I) of size classes with different settling velocities. The model then accounts for simultaneous size-selective deposition and non-selective re-entrainment from the loose layer of continuously deposited materials, based on the mass balance equation

$$\frac{\partial(qc_i)}{\partial x} + \frac{\partial(c_i D)}{\partial t} = d_i - r_{ri} \tag{1}$$

where q is surface water flux per unit width of slope (unit discharge), c_i is sediment concentration of size class i in the runoff, D is runoff water depth, x is downslope distance, t is time, d_i is the deposition rate of class i, and r_{ri} is the re-entrainment rate of class i. A detailed explanation of the model can be found in Hairsine et al. (2002). The key input determining the size-selectivity of sediment transport process is the size-specific settling velocity v_i, which controls the deposition rate of each particle size class. A number of solutions, both analytical and numerical, have been developed (Sander et al., 2002), and the model has been tested against sediment data from laboratory flume studies (Beuselinck et al., 2002) and spatial patterns of net deposition on catchment scales at different soil conditions (Fiener et al., 2008; Van Oost et al., 2004). The model was also used to assess the dependence of predicted size-selective sediment transport on the size distribution of source materials using artificially generated settling velocity distribution (SVD) data (Hogarth et al., 2004; Kim et al., 2016). However, there is a lack of field observations relating aggregate breakdown to changing soil and weather conditions and exploring the extent to which the FSD of breakdown products available for transport can change in the course of successive rainfall events.

In this study, we monitored how aggregate stability and FSD changed in an agricultural field over a period of several weeks with a sequence of artificial rainfall events of two different intensities. The objectives were (1) to assess the influences of repetitive wetting and drying on aggregate stability and FSD, and (2) to determine how the post-event FSDs resulting from rainfall-induced aggregate breakdown would affect size-selective sediment transport using the Hairsine et al. (2002) model.

2. Materials and methods

2.1. Field experiment

The rainfall experiments were carried out on a flat agricultural field site of the Zurich-Reckenholz station of the Swiss federal agricultural research institute Agroscope. With 18.6% clay, 57.0% silt and 24.4% sand, the study soil was a silt loam and classified as Cambisol according to World Reference Base taxonomy. The topsoil (0–5 cm) had an initial bulk density of 1.03 g cm^{-3}, pH (H_2O) of 7.2, and soil organic carbon content of 1.4%. Before the commencement of the experiments, the field was ploughed to a depth of 15 cm, and prepared as a seedbed.

In total, five artificial rainfall events with varying durations of drying periods in between were performed in two replicates each on neighboring plots over a period of approximately five weeks, applying a rainfall intensity of 25.8 mm h^{-1} (MR) in three events and a rainfall intensity of 49.1 mm h^{-1} (HR) in the other two events. During the times between rainfall applications, the soil surface was protected from natural rainfall by means of a waterproof plastic cover (Fig. 1). Space was kept on the sides between soil and cover to allow for ventilation, and the protective cover was removed on sunny days to allow natural drying processes to occur. At first, the two medium-intensity rainfall events MR1 and MR2 were applied on two consecutive days in late April 2015 (Table 1). The plots were then let dry for several days (D1), before the first high-intensity rainfall HR1 was applied. The last two rainfall events, MR3 and HR2, were each applied after two weeks of drying (D2 and D3) since the preceding rainfall event. The two replicates of each experiment were performed sequentially on the same day.

The artificial rainfall was produced a through an exchangeable nozzle mounted at a height of 3.6 m to ensure that rainfall uniformity