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Soil aggregate stability and size-selective sediment transport with surface runoff as affected by organic residue amendment

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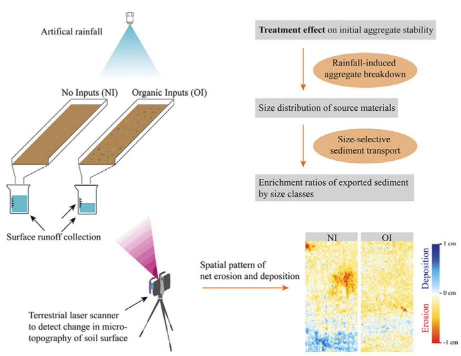
HIGHLIGHTS

- Organic amendment improved soil aggregate stability against rainfall-induced breakdown.
- Organic amendment led to reduced discharge.
- Reduced discharge led to lower sediment concentration in the runoff.
- The fraction of coarse sediments increased with increasing sediment concentration.
- Laser scanning revealed a less obvious change in surface roughness with the OI treatment.

GRAPHICAL ABSTRACT



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ABSTRACT

Aggregate breakdown influences the availability of soil particles for size-selective sediment transport with surface runoff during erosive rainfall events. Organic matter management is known to affect aggregate stability against breakdown, but little is known about how this translates into rainfall-induced aggregate fragmentation and sediment transport under field conditions. In this study, we performed field experiments in which artificial rainfall was applied after pre-wetting on three pairs of arable soil plots (1.5×0.75 m) six weeks after incorporating a mixture of grass and wheat straw into the topsoil of one plot in each pair (OI treatment) but not on the other plot (NI treatment). Artificial rainfall was applied for approximately 2 h on each pair at an intensity of 49.1 mm h^{-1}. In both treatments, discharge and sediment concentration in the discharge were correlated and followed a similar temporal pattern after the onset of surface runoff: After a sharp increase at the beginning both approached a steady state. But the onset of runoff was more delayed on the OI plots, and the discharge and sediment concentration were in average only roughly half as high on the OI as on the NI plots. With increasing discharge the fraction of coarse sediment increased. This relationship did not differ between the two treatments. Thus, due to the lower discharge, the fraction of fine particles in the exported sediment was larger in the runoff from the OI plots than from the NI plots. The later runoff onset and lower discharge rate was related to a higher initial aggregate stability on the OI plots. Terrestrial laser scanning proved to be a very valuable method to map changes in the micro-topography of the soil surfaces. It revealed a much less profound decrease in surface roughness on the OI than on the NI plots.

Abbreviations: OI, organic inputs; NI, no inputs; ER, enrichment ratio; TLS, terrestrial laser scanning; SOC, soil organic carbon; IWC, initial water content; FSD, fragment size distribution; SSD, sediment size distribution; DEM, digital elevation model; SRR, surface random roughness; D50, median diameter.

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1. Introduction

Soil aggregate stability is a major factor controlling soil erodibility (Barthes and Roose, 2002; Gumiere et al., 2009). Due to its influences on the extent of rainfall-induced aggregate breakdown, it is of particular relevance for the size characteristics of fragments available for sediment transport and deposition with surface runoff (Le Bissonnais, 1996). Under the erosive forces of rainfall, soil aggregates are disintegrated, releasing fine fragments that differ in size distribution, depending on the stability and composition of the aggregates (Legout et al., 2005; Yan et al., 2008). These products then become the source materials for sediment mobilization and export with rainfall splash and runoff wash (Wang and Shi, 2015). By clogging pores and forming surface crusts, fragments generated by aggregate breakdown at the soil surface also enhance runoff generation (Roth and Eggert, 1994).

The size-selective nature of sediment transport is well documented (Armstrong et al., 2011; Asadi et al., 2011; Martinez-Mena et al., 2002; Rienzi et al., 2013; Shi et al., 2012; Wang and Shi, 2015). As fine particles are more easily carried away than coarse particles due to their low settling velocities, sediments are increasingly enriched in clay- and silt-sized particles with transport distance in comparison to the source materials. A common measure to characterize and compare the size-selectivity of erosion processes is the sediment enrichment ratio (ER), which is defined as the ratio between the amount of exported sediment and the amount of source material for each size fraction. A shortcoming of many erosion studies on sediment ER is that the common methods to determine the size distribution of source materials at the onset of surface runoff do not account for all relevant factors controlling these distributions (Leguedois and Le Bissonnais, 2004). When determining ER, the most widely used procedure to quantify the size distribution of source materials is wet sieving, in which dry aggregates are immersed in water and thereby subjected to slaking (Asadi et al., 2011; Shi et al., 2012). Considering the products resulting from this procedure as the source materials available for size selective sediment transport, however, means that it neglects the roles of mechanical aggregate breakdown under rainfall impact (Ma et al., 2014) and of initial soil water content (Truman et al., 1990) in controlling the fragment size characteristics prior to the initiation of surface runoff.

An important factor determining aggregate stability that can be strongly influenced by agricultural management is soil organic matter. Valera et al. (2016) stated that improper land use could lead to a reduction in soil organic matter content, and thereby to accelerated erosion rates (Pacheco et al., 2014). To combat soil erosion, a number of studies have investigated the effectiveness of organic amendments under a variety of climatic and topographic conditions and across different spatial scales (Peng et al., 2016; Prosdocimi et al., 2016; Shi et al., 2013; Tejada and Gonzalez, 2007; Wei et al., 2017). Among others, crop residues such as wheat straw and green manure from intercrops have been used as soil amendments to enhance soil aggregate stability (Mulumba and Lal, 2008; Sadeghi et al., 2015). The effect of such amendments on aggregate stability depends on various factors, in particular those that determine their decomposition and include intrinsic biochemical properties such as the carbon (C):nitrogen (N) ratio, and the contents in glucose, cellulose and lignin (Abiven et al., 2009).

Only few studies investigated how organic residue inputs affect aggregate breakdown and size-selective transport of sediments in erosive rainfall events. Focusing on the mulching effects of organic matter applications, Cogo et al. (1983) and Shi et al. (2013) both found decreased sediment size with increasing surface residue cover. Shi et al. (2013) reported that increasing straw cover led to a shift from a transport-limited to a detachment-limited condition. In the study presented here we conducted artificial rainfall experiments on pairs of neighbouring agricultural field plots after incorporating a mixture of grass and wheat straw into the topsoil of one plot in each pair (OI treatment) but not into the other (NI treatment). The questions were (1) to what extent the organic residues would increase surface aggregate stability and thereby reduce aggregate breakdown during rainfall, (2) how this would translate into size-selective sediment transport, and (3) whether the two treatments thereby would lead to different effects on the micro-topography of the plots.

The micro-topography of the plots was monitored using terrestrial laser scanning (TLS). TLS is now frequently used in geomorphological studies to monitor landslides (Prokop and Panholzer, 2009), erosion and deposition processes (Nadal-Romero et al., 2015) and soil surface roughness (Thomsen et al., 2015). Having the capacity to provide spatial information with high resolution on changes in surface elevation as small as a few millimetres, it is well suited to obtain data that have not been available before for the development and validation of spatially explicit erosion models (Jetten et al., 2003).

2. Materials and methods

2.1. Experimental design

The artificial rainfall experiments were conducted in June and July 2016 on a gently sloping agricultural field located at the Zurich-Reckenholz station of the Swiss Federal Agricultural Research Institute (Agroscope). The soil was a silt loam (19% clay, 57% silt, and 24% sand) according to USDA classification. After ploughing the entire field to a depth of 15 cm, a seedbed was prepared and the slope was adjusted to 10% locally on three blocks selected for the experiment. On each block, two 2.5×1.25 m plots were delineated side by side, one for the OI and one for the NI treatment (Fig. 1a). The upper 5 cm of the soil of the two plots were excavated and sieved to aggregates smaller than 10 mm. The soil from the NI plots was filled back immediately after sieving, while the soil from the OI plots was mixed with the mixture of organic residues described below at a rate of 2.12 g C per kg soil before being filled back into the plots. The bulk density of the gently repacked soil averaged 1.21 ± 0.05 g cm^{-3} for both treatments.

The organic matter used for incorporation was a mixture of grass and wheat straw residues obtained from local farms. The residues had been dried at 60 °C, chopped into pieces of <1 cm size and thoroughly mixed at a grass:straw ratio of 2:1 by weight, resulting in a C content of 42%, an N content of 1.9%, and thus a C:N ratio of 22. The mixture of organic residues was incorporated into the excavated surface soil from the OI plots using a mini concrete mixer, taking care that a homogenous mix was achieved.

After organic residue incorporation, all plots were covered with waterproof plastic sheets to protect the soil surface from natural rainfall. Space was left between the cover and the soil surface for ventilation to ensure aerobic conditions (Fig. 1c). Each plot was watered with 20 L deionized water twice a week for six weeks. Thereafter an area of 1.5×0.75 m size was confined within each plot by pushing metal plates 7 cm into the soil. The plates were left to protrude 8 cm out of the soil to prevent surface runoff crossing the upper and lateral boundaries of the plots during rainfall (Fig. 1b). To collect the surface runoff from the confined area, a triangular trough with lateral connection to the metal plates was installed at the lower end of each plot.

2.2. Rainfall simulation

Prior to rainfall application, the two plots of each block were simultaneously pre-wetted by applying 32 L deionized water over 12 min using a spraying can to enhance the magnitude of slaking, simulating conditions that commonly occur at the beginning of rainfall events in the study region. Immediately after pre-wetting, artificial rainfall was applied onto both plots at a rate of 49.1 ± 0.8 mm h^{-1} through a rainfall simulator for approximately 2 h. Such a rainfall intensity was recorded twice in the year 2015 alone at a nearby weather station (MeteoSwiss), and a similar intensity has been used in rainfall simulation studies in similar regions (Hahn et al., 2012). The rainfall simulator consisted a nozzle (1/2 HH35W, Spraying Systems Fulljet) mounted to an