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Effect of soil surface roughness on infiltration water, ponding and runoff on tilled soils under rainfall simulation experiments

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ABSTRACT

Agriculture has a large effect on the properties of the soil and with that on soil hydrology. The partitioning of rainfall into infiltration and runoff is relevant to understand runoff generation, infiltration and soil erosion. Tillage manages soil surface properties and generates soil surface roughness (SSR) that affects the partitioning of the rainfall. The objective of this study was to quantify the amount of rainwater that infiltrates, is temporarily stored in surface depressions and flows out of the surfaces during rainfall events. A set of tillage-induced rough surfaces with slope steepness of 10° and 15° was used under simulated rainfall, and a smooth surface served as a control. Rainfall intensities were 60 and 120 mm h^{-1}, and two soil erosion periods, overland flow erosion period (OFEP) and rill flow erosion period (RFEP), were monitored for each rainfall intensity. The results showed that for OFEP, infiltration water was 58% and 76% of the total rainwater on the rough surfaces and was approximately 1.5 and 2 times greater than that on the smooth surfaces for the different rainfall intensities. The surface runoff was consistently small for the OFEP but significantly increased for the RFEP. For example, for the RFEP, the amount of surface runoff was up to 78.66% of the total rainwater on the rough surfaces under rainfall of 120 mm h^{-1} in intensity. The amount of rainwater stored in surface depressions was significantly less than infiltration water and surface runoff for all conditions. The mean transformation ratio of rainwater into surface depression storage, infiltration water and surface runoff in the OFEP and RFEP was 0.07:0.49:0.44 for the rough surfaces and 0.01:0.29:0.70 for the smooth surfaces. For the tilled surfaces, more than 50% of rainwater was be harvested through tillage technique during a rainfall event, whereas for the smooth surfaces, only 29% of rainwater. Our result will be useful when evaluating the impact of tillage on soil moisture content and even studying soil erosion in agriculture land.

1. Introduction

Agriculture has a large effect on the properties of the soil and with that on soil hydrology (Cerdà et al., 2009; Bruun et al., 2015; de Oliveira et al., 2015; Colazo and Buschiazzo, 2015). The partitioning of rainfall into infiltration and runoff is relevant to understand runoff generation, infiltration and soil erosion (Van Eck et al., 2016; Wang et al., 2016; Zema et al., 2016). Tillage manages the soil surface properties and generate soil roughness that affect the partitioning of the rainfall (Novara et al., 2011; Balota et al., 2016; Römkens et al., 2002). Soil surface roughness (SSR) is a common index used to quantify the micro-relief characteristics of tilled surfaces (Römkens and Wang, 1986; Hansen et al., 1999). In the past few decades, many studies have been conducted to measure the spatial heterogeneity of SSR and to analyse the effect of SSR on soil erosion at field and plot scale (Takken et al., 2001; Le Bissonnais et al., 2005; Strudley et al., 2008). SSR plays a key role in runoff generation and soil particles detachment. For example, the spatial heterogeneity of SSR causes localized surface storage and infiltration capacities that differ from those of smooth surfaces and therefore affects surface runoff and erosion characteristics of rough surfaces (Zhao et al., 2016a). The SSR can act similar as a mulch or vegetation cover as it reduces the surface wash velocity and increase the infiltration rate (Keesstra et al., 2012; Prosdocimi et al., 2016; Zhao et al., 2016b).

In arid areas, rainwater is the main source of soil water and the water needed by plants. In agricultural lands, water stored in the deeper layers (more than 30 cm) of soil be utilized by plants. Therefore, it is essential that rain water will be stimulated to infiltrate after rainfall

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Table 1
Physio-chemical properties of the experimental soil at 0–20 cm of depth.

Organic matter	Total N	Total P	CEC	Soil particle size (mm)					
				< 0.001	0.001– < 0.005	0.005– < 0.01	0.01– < 0.05	0.05–0.25	> 0.25
g kg^{-1}			cmol kg^{-1}	%					
16.66	0.91	0.50	18.47	36.28	12.89	6.88	41.33	2.70	0.12

through water harvesting techniques. Special tillage practices have been designed for this purpose in many parts of the world. These tillage practices alter soil micro-reliefs and the infiltration capacity of the soil, which allows the increased rainwater transformation in infiltration and a subsequent decrease in surface runoff. This is a strategy that imitates the natural ponding that would occur in a well-developed soil with vegetation cover, which would allow water to be retained on sloping land (Mekonnen et al., 2015a,b; Grimaldi et al., 2015; Lasanta et al., 2016). In natural well developed and covered soils the infiltration capacity is very high, and almost all rainwater infiltrates at the beginning of rainfall events (Cerdà, 1997) unlike in bare soils such as badlands (Cerdà, 1999). However, the rate of soil infiltration decreases gradually with increasing cumulative rainfall. Once the infiltration rate is lower than the rainfall intensity, the excess rainwater either contributes to runoff or is stored in surface depressions. With rainwater increasing, more and more surface depressions are fully filled, and the stored rainwater begins to flow out of the depressions from their 'pour points' and further increases the amount of surface runoff. In turn, surface runoff leads to depression failure and flow path formation on the soil surfaces, hence reducing depression storage capacity and potential infiltration of rainwater. The discussion above shows that soil infiltration, depression storage and surface runoff are the three important sub-processes that can directly or indirectly influence each other during rainfall, runoff, and erosion processes. SSR's effect on rainfall, runoff, and erosion processes is reflected by its effect on surface storage capacity, soil infiltration capacity and runoff amount.

Surface storage capacity describes depressional storage, which can be calculated using various empirical equations containing SSR indices or indirectly estimated using digital techniques based on DEMs. However, for different SSR indices and the resolution of DEMs, the amount of surface depression storage calculated differs. Guzha (2004) showed that the higher the surface roughness, the greater the depressional storage on tilled surfaces. For the different tillage practices, the depressional storage differs. The runoff initiating time of rough surfaces is longer than that of smooth surfaces as a result of the depressional storage. The confluence of runoff water and the development of rill networks are significantly different among surfaces with different initial SSR (Gómez et al., 2003).

Regarding the role of SSR in surface runoff, there are two different views: Some studies have suggested that SSR can reduce runoff due to the depressional impact (Burwell and Larson, 1969; Onstad, 1984; Steichen, 1984), while other studies have proposed that the effect of SSR on the runoff amount is limited (Helming et al., 1998; Gómez and Nearing, 2005). They have even noted that a rough surface can produce more runoff than can a smooth surface under certain conditions. Furthermore, Darboux and Huang (2005) suggested that the effect of SSR on the runoff amount was related to the contributing area of runoff. Once the runoff hydrograph reaches a plateau, the whole surface becomes a contributing area of runoff. Only in this condition the total runoff amount from rough and smooth surfaces is the same. Therefore, they noted that SSR's effect on surface runoff only appeared in the early stage of rainfall.

Much research has explored the mechanisms of SSR impacting infiltration, depression storage and surface runoff during rainfall. However, few studies have quantified simultaneously the proportions of rainwater becoming infiltration water, depressional storage and surface runoff in a rainfall event. In other words, to assess the transformation ratios of rainwater to infiltration water, depressional storage and surface runoff, it would be beneficial to understand SSR's contribution to soil and water conservation and water availability for agriculture in arid areas.

The objective of this study was to assess the effect of SSR on rainwater distribution by quantifying the proportions of rainwater becoming infiltration water, depressional storage and surface runoff during a rainfall events of different intensities and rainfall event length and on different slopes.

2. Materials and methods

2.1. Soils

Top soil (0–20 cm depth) was collected from farmland at Yangling (34°17′56″N, 108°04′07″E), Shaanxi Province, China. The site has a temperate semi-humid climate with a mean annual temperature of 13 °C, annual potential evaporation of 1400 mm per year, and precipitation of 620 mm that is distributed unevenly throughout the year. Most rainstorms occur in summer, when sudden storms with rainfall intensities of more than 100 mm h^{-1} are usual. The farmland had been cultivated continuously for more than 10 years. The soil is classified as a Eum-Orthic Anthrosol. The physical and chemical properties of soils are listed in Table 1.

2.2. Experimental design

Experiments were performed in soil boxes of 2.0 m in length by 1.0 m in width by 0.5 m in depth. At the downslope end of each box was a V-shaped drainage outlet, which was used to collect surface runoff. The testing slope gradients were 10° and 15°. The rainfall intensities in the rainfall experiments were 60 and 120 mm h^{-1}. Two types of soil surface treatments (rough vs. smooth) were prepared for rainfall testing. A total of four experimental treatments were carried out for each one of two rainfall intensities: 1) rough surface with 10° slope (R10), 2) smooth surface with 10° slope (S10), 3) rough surface with 15° slope (R15) and 4) smooth surface with 15° slope (S15).

Soil surface heights for each slope were measured before and after simulated rainfall event using a laser microrelief meter, which the details have been descripted and found in the previous study by Zhang et al. (2014). Then, the laser data were used to analyse surface depression storage and soil infiltration.

Each treatment was repeated 3 times. For each run, soil boxes were prepared with fresh soils.

2.3. Soil preparation in boxes

Before soil preparation in the boxes, the soils were sieved through a 10-mm sieve to ensure homogeneity, and the soils were then air-dried in the laboratory. During soil preparation in the boxes, each box was filled with air-dried soils in successive layers of 0.05 m in thickness. In this study, the total thickness of backfill soils in each box was 0.4 m. The bulk density of the soil layers in each box was 1. 30 g cm^{-3}, which is close to the bulk density of natural soil layers under field conditions. After each box was filled with soil, the soil surface was evened using a