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Contribution of raindrop impact to the change of soil physical properties and water erosion under semi-arid rainfalls

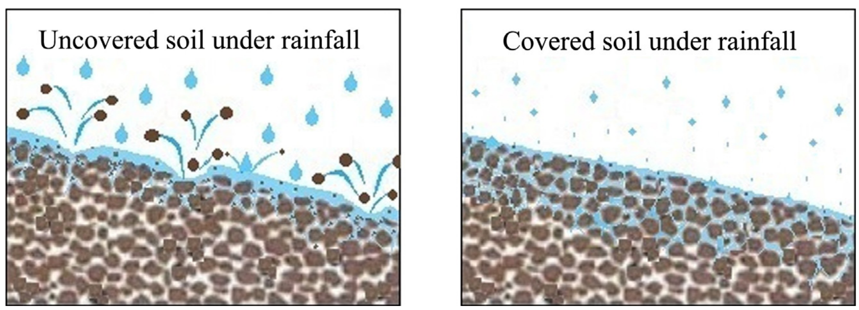
Ali Reza Vaezi [a,*], Morvarid Ahmadi [a], Artemi Cerdà [b,c]

[a] Department of Soil Science, Agriculture Faculty, University of Zanjan, 45371-38791 Zanjan, Iran
[b] Soil Erosion and Degradation Research Group, Department of Geography, University of Valencia, Valencia, Spain
[c] Soil Physics and Land Management Group, Wageningen University, Droevendaalsesteeg 4, 6708PB Wageningen, The Netherlands

HIGHLIGHTS

- Higher contribution of raindrop impact to change of soil properties in agriculture land
- Increasing the change of soil properties by raindrop impact with increasing rainfall intensity
- Higher dependency of water erosion on the change of soil physical properties by raindrop impact
- Higher contribution of raindrop impact to produce runoff and water erosion in agriculture soil
- Lower contribution of raindrop impact to soil erosion in higher rainfall intensities

GRAPHICAL ABSTRACT



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ABSTRACT

Soil erosion by water is a three-phase process that consists of detachment of soil particles from the soil mass, transportation of detached particles either by raindrop impact or surface water flow, and sedimentation. Detachment by raindrops is a key component of the soil erosion process. However, little information is available on the role of raindrop impact on soil losses in the semi-arid regions where vegetation cover is often poor and does not protect the soil from rainfall. The objective of this study is to determine the contribution of raindrop impact to changes in soil physical properties and soil losses in a semiarid weakly-aggregated agricultural soil. Soil losses were measured under simulated rainfalls of 10, 20, 30, 40, 50, 60 and 70 mm h^{-1}, and under two conditions: i) with raindrop impact; and, ii) without raindrop impact. Three replications at each rainfall intensity and condition resulted in a total of 42 microplots of 1 m × 1.4 m installed on a 10% slope according to a randomized complete block design. The contribution of raindrop impact to soil loss was computed using the difference between soil loss with raindrop impact and without raindrop impact at each rainfall intensity. Soil physical properties (aggregate size, bulk density and infiltration rate) were strongly damaged by raindrop impact as rainfall intensity increased. Soil loss was significantly affected by rainfall intensity under both soil surface conditions. The contribution of raindrop impact to soil loss decreased steadily with increasing rainfall intensity. At the lower rainfall intensities (20–30 mm h^{-1}), raindrop impact was the dominant factor controlling soil loss from the plots (68%) while at the higher rainfall intensities (40–70 mm h^{-1}) soil loss was mostly affected by increasing runoff discharge. At higher rainfall intensities the sheet flow protected the soil from raindrop impact.

* Corresponding author.
E-mail addresses: vaezi.alireza@gmail.com, vaezi.alireza@znu.ac.ir (A.R. Vaezi), artemio.cerda@uv.es (A. Cerdà).

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1. Introduction

Soil erosion by water has been recognized as one of the most important worldwide environmental problems (Mhazo et al., 2016; Zhang et al., 2017), including in semi-arid agricultural lands (Ochoa et al., 2016; Vaezi et al., 2016a) where soil erosion can endanger crop production due to damages to soil quality (Vaezi and Bahrami, 2014). Soil erosion can also change the fate of the carbon cycle (Uri, 2000) and disturb the Earth hydrological, erosional, geochemical and biological cycles due to the soil degradation (Keesstra et al., 2012; Brevik et al., 2015) and also affect the services, goods and resources the soil system offers, which is a key issue for the United Nations Goals to achieve the sustainability (Keesstra et al., 2016).

The soil degradation is a consequence of the bare or scarcely covered soils in semiarid lands, but is also due to mismanagement as a consequence of traditional intense tillage, use of heavy machinery, widespread application of herbicides and traffic in the fields, tracks, and roads (Gessesse et al., 2015; Parras-Alcántara et al., 2016; Rodrigo Comino et al., 2016). The high erosion rates in agriculture land are due to the lack of vegetation cover, which is the key factor to understand soil erosion process (Cerdà, 1999; Ola et al., 2015; Zhao et al., 2016). Degradation of structure is a type of physical soil degradation which is usually related to agriculture practices, particularly to soil tillage. Several authors have observed a loss of soil aggregation under the influence of cultivation (Cerdà, 2000; Annabi et al., 2011), which frequently involves a decrease in soil organic matter contents (Barral et al., 2007) and an increase in soil erosion (Barthes and Roose, 2002; Wang et al., 2016). Soil erosion accelerates land degradation, reduces ecosystem fertility, triggers desertification processes, and reduces services ecosystems offered to humankind through the soil system (Brevik, 2009; Mol and Keesstra, 2012; Symeonakis et al., 2016).

Approximately 40% of the world's land surface is classified as arid or semi-arid regions. About 35% of the lands in semi-arid areas are used for agricultural purposes. In these regions, lands with little or no vegetation cover are exposed to torrential precipitation events. These soils often have relatively low organic matter content and are weakly aggregated, especially under intensive agricultural practices (Cantón et al., 2009; Vaezi and Bahrami, 2014; Carr et al., 2015). Soil structure is easily broken by the impact of raindrops resulting in the formation of crust at the soil surface and increasing runoff and soil erosion rates (Cerdà, 2000).

Soil erosion processes are mainly caused by two mechanisms: raindrop impact and surface wash resulting from water in excess of infiltration (Ellison, 1947). When raindrops impact the soil surface, raindrop energy is used to overcome the bonds that hold together particles in the soil surface (Ma et al., 2014). Raindrop impacts break soil aggregates at the soil surface, and small soil particles are released (McIntyre, 1958). Rainfall may disrupt soil aggregates by two processes: slaking and raindrop impact. Slaking is the breakdown of soil aggregates into smaller sized micro-aggregates when immersed in water. The second process that may disrupt aggregates is the mechanical breakdown of soil aggregates by the hammering impact of falling raindrops. Two different situations occur during rainfall: 1) if aggregates are saturated before rainfall, breakdown intensity is due to contact between water and aggregates, and the most important processes are slaking and cracking; and 2) when aggregates are dry before rainfall, the breakdown intensity is due to rainfall kinetic energy and the most important process is mechanical breakdown or splash erosion (Le Bissonnais and Singer, 1993). The released soil particles by rainfall may then be displaced and reoriented into a more continuous structure by the infiltrating water, forming a surface seal (Ramos and Pla, 2003). This process is called 'washing in' and was already described by McIntyre (1958). Sealing is the disintegration of structural elements by slaking or dispersion leading to infilling of the interaggregate pores or by welding aggregates into larger units (Cerdan et al., 2001). Soil crusts mainly consist of a compacted top skin approximately 0.1 mm in thickness, and a 1.5 to 3.0 mm-thick washed-in deeper region of decreased porosity (Chahinian et al., 2006). The formation of crust at the soil surface due to the impact of raindrops is a common feature of cultivated soils in many regions of the world. Crusts affect runoff generation processes by decreasing surface saturated hydraulic conductivity (Ks) and subsequently also water infiltration (Stolte et al., 1997; Kidron, 2007), with this impact most significant in silt-rich soil (Robinson and Woodun, 2008). The influence of sealing on erosion processes has been studied by different authors (Le Bissonnais and Singer, 1993; Levy et al., 1994; Morin and Winkel, 1996; among others) in different soils, and several authors have reported that runoff and erosion susceptibility are linked to aggregate stability, especially in Mediterranean and tropical areas (Barthes and Roose, 2002).

The detached soil particles can be transported by surface runoff and splash, and this process constitutes the interrill erosion (Ben-Hut and Agassi, 1997; Lu et al., 2016). A soil surface exposed to rainfall is subjected to processes of wetting and drop impact which can lead to the formation of a seal during the rainfall, reducing infiltration and increasing erosion by increasing runoff (Ramos and Pla, 2003). Morgan (2005) reported that soil erosion by water is a two-phase process that consists of detachment of soil particles from the soil mass by rainsplash and transportation of detached particles by running water (surface runoff). Rainsplash erosion is caused by the kinetic energy of raindrops that strike the soil and throw particles into the air (Wischmeier and Smith, 1978; Sempere-Torres et al., 1994). Young and Wiersma (1973) showed that the transportation of detached soil particles occurs mostly by surface flow, rather than by rainsplash. Kinnell (2005) noted that four detachment and transport systems exist for soil erosion by water: i) raindrop detachment with transport by raindrop splash (splash erosion); ii) raindrop detachment with transport by raindrop induced flow transport. Rain-impacted flows are largely responsible for erosion in sheet and interrill erosion areas; iii) raindrop detachment with transport by flow, which causes mostly sheet erosion; and, iv) flow detachment with transport by flow, which is the most dominant mechanism of rill erosion.

Together with wind, rainfall is the most important active agent of soil erosion due to its potential to breakdown aggregates, detach soil particles, and produce runoff (Oliveira et al., 2013). The potential of rain to erode soil is known as rainfall erosivity (Meshesha et al., 2016). Rainfall erosivity can be evaluated using the ability of a given rain to detach soil particles and produce runoff flow (Angulo-Martínez et al., 2016). It includes the contribution of two erosive factors: raindrop impact and rain-induced flow. The kinetic energy of raindrops causes surface sealing and crust formation that reduces soil infiltration and produces surface flow, and this is why vegetation is the best soil erosion control strategy (Francos et al., 2016). It depends directly on the rainfall's kinetic energy. Kinetic energy is a commonly suggested indicator of a raindrop's ability to detach soil particles from the soil mass (Morgan, 2005). Intense rainfall events are usually associated with increases in both the number and size of raindrops (Lu et al., 2008). Runoff is an important factor controlling soil erosion in sloping areas as it determines how much of the detached material is transported (Strohmeier et al., 2016). Runoff production is affected by various factors such as soil properties, topographic characteristics, vegetation cover and rainfall characteristics. Among the rainfall characteristics, rainfall intensity and duration are the two major factors controlling runoff in each event (Ran et al., 2012). Different indices have been proposed to estimate the rainfall erosivity of an area using rainfall characteristics (intensity, kinetic energy, etc.) (Wischmeier and Smith, 1978; Lal, 1976; Hudson, 1971; Renard et al., 1991; Usón and Ramos, 2001). In some cases, runoff characteristics (volume, peak discharge, etc.) have been also used to explore rainfall erosivity at the event scale (Williams, 1975). Rainfall erosivity can be also defined for each type of soil erosion by water (splash, interrill, rill, etc.) in a rainfall event. For example, Nearing et al. (1989) used the square intensity of rainfall (I^2) and the flow shear stress (τ) as erosive indices for predicting soil loss at the event scale for rill flow