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Research paper

Interaction of land use, slope gradient and rain sequence on runoff and soil loss from weakly aggregated semi-arid soils

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ABSTRACT

The effects of land use, tillage methods and slope gradient on soil erosion have been widely investigated. However, there is limited information about their effects on very weakly aggregated soils that can be found in semi-arid, nutrient limited regions of low productivity. This study was carried out to investigate the interaction of land use, tillage method and slope gradient on runoff and soil loss in a weakly aggregated soil in the north-west of Iran. Plots (3 m × 10 m) with three treatments and two replicates were installed in each of four slopes gradient categories (12.6, 15.3, 17.0, 19.4%). The three treatments were pasture with poor vegetation cover (27%) and rainfed wheat either cultivated up to down slope or along the contour. Wheat was sown in early autumn and runoff and soil loss was measured under natural rainfall during the eight months long growing period. Out of 53 precipitation events, 8 storms were classified erosive. The susceptibility of all plots to produce runoff and soil loss increased pronouncedly and highly significantly with subsequent rainfalls. The potential of a rainfall to produce runoff and soil loss was thus highly dependent on preceding rainfalls. Wheat cultivation increased runoff 13 times and soil loss 60 times compared to pasture. Runoff and soil loss increased about 5.5 and 35 times in plots cultivated up to down slope as compared with contour cultivated plots. The effects of land use increased pronouncedly with increasing slope gradient. These results showed that erosivities of rainfalls separated by several months were not independent from each other and that the effects of land use and slope gradient interacted. Also the effect of slope gradient on soil loss was much larger than estimated by current equations. All effects could be explained by the extremely weak aggregates. Soil erosion was thus not detachment limited but transport limited. Transport limitation decreased in the sequence of rainfalls due to loss of surface roughness and with increasing slope gradient due to increasing failure of roughness elements. Under conditions leading to extremely weak soil aggregates, land use and slope gradient thus exert a much larger impact on runoff and soil loss than what is commonly assumed. This should be better considered in soil conservation efforts but also in runoff and erosion modelling.

1. Introduction

Water erosion has been recognized the most important factor of land degradation worldwide and particularly in arid and semi-arid regions (Breshears et al., 2003; Khalili Moghadam et al., 2015; Vaezi et al., 2016a). These regions cover about 41% of the Earth's land surface (UN, 2011). Semi-arid regions may suffer dramatic increases in erosion due to increasing population pressure and the conversion from pasture to crop production (Yüksek et al., 2010). For instance, in Iran soil erosion dramatically intensified and its rate increased from 3.0 to 24.3 tons ha^{-1} $year^{-1}$ within 50–60 years (Nosrati et al., 2011). In consequence, soil and water conservation is an important issue particularly in arid and semi-arid regions. Soil management through optimum tillage methods is regarded essential to control soil and water losses as well as improve soil water storage in these regions (Baig et al., 2013; Busari et al., 2015). Yet in many rainfed lands in semi-arid regions, ploughing is done up-and downward in the direction of the slope, while tillage perpendicular to the gradient would increase surface roughness in flow direction and detention storage (USDA-ARS, 2008; Lal, 1990; Stevens et al., 2009). This would increase rainwater infiltration, which in turn decreases soil detachment, runoff and soil erosion (Baig et al., 2013; Liu et al., 2014).

Many semi-arid areas have a low productivity because of the low rainfall but also because of a low nutrient availability (Bationo and Mokwunye, 1991; Chaghazardi et al., 2016) and weakly aggregated structure (Vaezi and Bahrami, 2014). Low productivity together with

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pressure to utilize above-ground biomass then leads to a low input of organic matter into the soils. Organic matter is well known to be of major importance for aggregation and aggregate stability (Bationo and Mokwunye, 1991; Bronick and Lal, 2005) especially when clay content is low which is typically found in semi-arid areas due to weak soil development (Rasmussen et al., 2010; Yousefifard et al., 2015). Furthermore, biological activity near the soil surface is restricted in semi-arid areas due to long periods during which the uppermost soil is dry. Taken together, a low aggregate stability can be expected for many semi-arid soils.

Soil erosion is the detachment of small soil particles and their transport mainly by runoff. Soil erosion can either be detachment limited or transport limited and factors influencing soil loss usually either influence detachment or transport capacity or both. E.g., with increasing soil cover, rain-drop impact on the soil surface is reduced. As a result detachment is reduced but at the same time infiltration may be higher due to less surface sealing and raindrop induced flow transport (Kinnell, 2005). Thus, also transport capacity is reduced with increasing soil cover.

Mainly raindrops, but also runoff shear, provide the forces to detach transportable soil particles. These forces have to overcome the binding forces within soil aggregates as usually quantified in aggregate stability. Detachment increases with decreasing aggregate stability and, in turn, erosion limitation by detachment decreases. It can hence be expected that the ratio of detachment limitation to transport limitation differs in weakly aggregated soils from those in better aggregated soils. Parameters influencing soil loss like soil cover or slope gradient may then have a different influence in semi-arid areas with poorly aggregated soils than in humid areas with better aggregated soils. Knowledge of such differences is important for understanding and predicting soils loss in semi-arid areas.

This study was carried out to analyze the interaction of land use, tillage method and slope gradient on runoff and soil loss in a weakly aggregated soil in NW Iran examining the hypothesis that transport limitation is more important than detachment limitation under these conditions. As a reference, the results will be compared with the effects predicted by the Revised Universal Soil Loss Equation (RUSLE, Renard et al., 1997; USDA-ARS, 2008), which was mainly developed in humid areas, where aggregate stability differs from that found NW Iran.

2. Materials and methods

2.1. Description of study area

About 642,797 km^2 of Iran (39% of the country) is semi-arid with an annual precipitation between 200 and 500 mm (Vaezi et al., 2016a). Soil erosion by water is a major environmental concern and can be observed as sheet, rill, gully and stream erosion (Vaezi et al., 2016b; Haddadchi et al., 2014; Nosrati et al., 2015). Soils are often calcareous with weakly aggregated structure and susceptible to water erosion (Feiznia and Nosrati, 2007; Vaezi, 2014). Poor vegetation cover as well as land use change from pasture to arable, along with improper soil management can commonly be found in this area. The virgin lands are located in steep slopes and they are used as a poor pasture for livestock in early spring. Where precipitation is sufficient, they are converted to arable land. The arable land is used mostly for production of rainfed crops such as winter wheat. Surface runoff and soil loss are high in early spring, when rainfalls are intensive and wheat cover is still poor. As a consequence, the change of virgin lands to rainfed cropping and cultivation along the direction of slope causes land degradation in these areas.

The study site was a 4 km^2 area located between 36°41′ to 36°45′N and 48°27′ to 8°56′E, in Zanjan, NW Iran (Fig. 1). The climate is semi-arid with a mean annual temperature of 10.9 °C and an average annual precipitation of 295 mm yr^{-1}, mostly falling as snow during winter and as rain in autumn and spring. The soils are Entisols and Inceptisols with shallow A horizons (Vaezi et al., 2016b). The region is dominated by 5% to 25% slopes, which are used for grazing for a short period in early spring. Arable land is mainly used for winter wheat production under rainfed condition with an average yield of 0.9 t ha^{-1} yr^{-1}. Winter wheat contributes about 92% of total grain production in this region (Vaezi et al., 2016a). The soils of the study area are poor and infertile and the amounts of N (0.08 mg kg^{-1}), P (9.4 mg kg^{-1}) and K (16.4 mg kg^{-1}), Fe (3.1 mg kg^{-1}), Mn (0.47 mg kg^{-1}), Zn (0.19 mg kg^{-1}) and Mo (0.26 mg kg^{-1}) are much lower than their optimum levels for wheat production (Shabani, 2014). Thus, wheat production is limited by both water deficit and the shortage of macro and micronutrients.

2.2. Installation of erosion plots and measurements

The field experiment was carried out in a pasture area with short hillslope lengths and poor vegetation cover. The dominant pasture species was *Rosa persica* J.F. Gmel., which covered about 27% of the soil surface. Four uniform slopes with gradients of 12.6, 15.3, 17.0 and 19.4% were selected. Six erosion plots, 3 m wide and 10 m long with a 1-m interval, were installed on each of the four slopes and subject to three management methods with two replicates (in total 24 plots). The three management methods included pasture with natural vegetation cover, pasture converted to rainfed wheat cultivated along the contour, and pasture converted to rainfed wheat cultivated along the slope. Tillage involved moldboard ploughing to a depth of 25–30 cm and disking followed by a field cultivator to prepare a smooth seedbed.

The upper, left and right sides of each plot were surrounded by 30-cm soil ridges to prevent runoff inflow into the plot. At the bottom side, a galvanized, triangle shaped steel gutter channeled the entire runoff through a PVC tube, which was attached to a 10-cm hole at the vertex of the gutter, into a 60-L plastic barrel (Vaezi et al., 2008) (Fig. 2). The amount of rain falling on the gutter was subtracted from the total runoff to determine net runoff of the plot.

Surface runoff and soil loss were measured after each erosive rainfall event for nine months during the growing period between October 2013 and June 2014. The volume of the mud-water mixture in the runoff ; ;-collecting barrel was determined using a graduated container, and then stirred thoroughly; aliquots were collected, and dried at 105 °C for 48 h.

2.3. Determination of soil properties

Soil samples from 0 to 30 cm depth were taken randomly at three locations within each plot before ploughing, combined and air-dried. A total of twenty four composite samples were collected from four lands under three management methods at two replications. Aggregates 6 mm to 8 mm in size were separated for aggregate analysis. The remainder was ground to pass through a 2-mm sieve. The particle size distribution including gravel (2–8 mm), sand (0.05 mm to 2 mm), silt (0.002 mm to 0.05 mm) and clay ($<$ 0.002 mm) was determined by a combination of sieving and the hydrometer method (Gee and Bauder, 1980). Aggregate stability was determined as mean weight diameter (MWD) after wet-sieving following Angers and Mehuys (1993) using 100 g of aggregates and 1 min agitation time. This short period was chosen because the aggregates were very unstable and they were destroyed entirely by movement in water for the conventional 30 min with 20 rotations per minute. One minute was considered best to distinguish differences in aggregate stability among various treatments. Soil infiltration rate was measured with a double-ring infiltrometer (Bouwer, 1986) with two replicates in each slope steepness category. Soil pH and electrical conductivity (EC) were measured in a soil-water suspension (1:2) using a digital pH meter and an EC meter. Cation exchange capacity was measured by the ammonium acetate method (Gillman et al., 1983). Exchangeable sodium percentage was calculated from exchangeable cations. Total soil organic carbon was measured by