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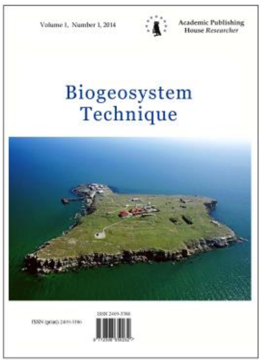

The Science and the Problems of Development

UDC 55

Soil Structural Stability and Erosion in a Semi-arid Agro-ecosystem

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Abstract

Soil erosion and subsequent pollution by water from agricultural lands or watersheds is still in need for evaluating of the impacts of various spatio-temporal processes involved. We have summarized the contribution of soil inherent properties (predominant clay mineralogy, soil texture, and organic matter content), and extrinsic conditions (rain kinetic energy [KE], wetting rates [WR], water quality, antecedent moisture contents, tillage intensity, soil sodicity [ESP], amendments) on soil structure deterioration and erosion (runoff and soil loss) from numerous cultivated semi-arid soils. Soil loss from predominant smectitic soils was up to several times higher than from kaolinitic soils. Soil erosion seems to increase exponentially with the increase in rain KE, WR and ESP and decrease in clay content and organic matter. Rain KE and water quality (sealing, physicochemical clay dispersion) prevailed in determining erosion in medium- and coarse-textured soils, and WR (prevention of aggregate slaking) played a predominate role in fine-textured soils. Effects of minimum-tillage were soil texture and irrigation water quality dependent: erosion was notably lower under no-tillage than under conventional one, being more affective in clayey soils with stable structure, for both fresh and effluent water quality. Soils, having moisture content in the range between wilting point and field capacity were less susceptible to runoff generation and erosion. Application of a small amount of polymer in combination with gypsum may effectively decreased soil erosion. Whereas inherent soil properties cannot be changed, conditions prevailing in the soil (WR, moisture content, impact of rain KE) can be manipulated by management practices to arrive at conditions that decrease soil susceptibility to soil erosion and subsequent water quality problems. Results may assist in improving our understanding of the changes in the degree of erosion in semi-arid zone soils, and can be employed in modeling efforts aimed at the prediction of soil erodibility.

Keywords: permanent properties and extrinsic conditions, soil system, infiltration, runoff, erosion, modeling

Introduction

Soil loss by overland flow in agricultural watersheds is a severe problem worldwide because (i) a non-renewable productive soil resource is being lost, and (ii) runoff and eroded sediments are a potential source of both point and non-point pollution that could degrade water quality in river systems and contaminate downstream areas (Sharpley et al., 2006). In many semi-arid lands runoff is initiated or enhanced by seal formation at the soil surface. Soil structure deterioration and seal formation in soils exposed to rain or overhead irrigations systems results from two complementary mechanisms: (i) physical disintegration of surface aggregates and their compaction by the impact of the waterdrops, and (ii) a physico-chemical dispersion and movement of clay and other fine-sized particles down the profile to 0.1–0.5 mm depth, where they may accumulate and clog water conducting pores (Agassi et al., 1981). However in soils which considerable protected with plant residue material, in stable clay or kaolnitic soils, runoff generation and sediment transport could results from saturation of soils (Lado and Ben-Hur, 2004). Such problems are expected to become more severe with climate change (e.g. runoff generation and sediment and pollutant transport under rain with high intensity). Generally, soil interrill erosion by water involves also two main processes: (i) detachment of soil material from the soil mass by waterdrops (commonly raindrops) impact and/or runoff shear, and (ii) transport of the resulting sediment by water drops splash and/or flowing runoff water. Raindrop detachment is greater than flow shear detachment because the kinetic energy of raindrops is much higher than that of surface flow. However, movement of detached soil down slope by rain splash is minimal, and most of the sediments are removed from the interrill area by runoff flow. Meanwhile, under certain management, soil or topographic conditions (disturbed soils, hill slope, soil with high dispersion potential, etc.), runoff flow may be sufficient for soil detachment and transport (Levy et al., 1994; Mamedov et al., 2002; van Oudenhoven et al., 2015).

Results from a large body of research on soil erosion suggests that runoff generation, sediment detachment and transport (i.e. when irrigation water and precipitation rate exceeds the infiltration capacity of the soil, Hortonian runoff sediment transport) may be quiet substantial during high rain-intensity events. Usually, only a portion of the agricultural field or watershed that are susceptible to becoming saturated, generates runoff and erosion and contributes sediments to the streams. Agricultural fields usually exhibit a complex spatial and temporal variability related to soil and management characteristics, and hence serves as variable sources of sediment and pollutant, and hydrologically sensitive areas with a high tendency for generating overland flow, where runoff provides quick transport mechanism for potential pollutants between the landscape and surface water bodies (Walter at al., 2000; Garcıa Ruiz, 2010). Therefore watershed-scale erosion and water quality efforts are considered to be focused on those areas that potentially contribute erosion and pollutants after sealing and/or saturation or combination of both (Gburek et al., 2002). Moreover, agricultural management practices also affect soil properties and off-site impacts of agriculture by influencing soil hydraulic characteristic, and sensitivity to runoff, and erosion (Tomer et al., 2006; Rhoton et al., 2002; Canton et al., 2011). Thus, the contribution of these runoff generating sources may increase and decrease depending on spatio-temporal variability, which is associated with agricultural management, soil intrinsic properties and condition (clay type, texture, organic matter, tillage, plant residue, drainage, crop rotation, amendments, antecedent moisture, rain intensity, etc.) (Walter et al., 2000; Sharpley et al. 2006; Norton et al., 2006; Garcıa Ruiz, 2010).

The processes that control sediment and dissolved pollutants transport could differ, but are however linked; pollutants are susceptible to transport whenever runoff water flows through or from an area loaded with pollutants (Qui et al., 2007). Most of the currently used risk assessment models, cannot adequately handle the complexity of the conditions prevailing in the field, probably at least in part due to lack of understanding of how soil properties and conditions prevailing in the field affect soil structure decline, runoff generation in a watershed, and the subsequent transport of sediments and chemicals (Gburek et al., 2002; Sharply et al., 2006; Mamedov et al., 2006). Our **objective** was to evaluate in a systematic manner the combined effects of semi-arid soils permanent properties and conditions on runoff generation and erosion, so that to gain a better insight into this complex topic and develop suitable management practices to minimize loss of sediments and/or transport of nutrients having a significant pollution potential.

Materials and Methods

The contribution of soil inherent properties and extrinsic conditions (Israel and USA) on soil erosion was studied systematically in many cases using rainfall simulators. A detailed description of the experimental setup can be found in various studies (Mamedov et al, 2000). Soil inherent properties that were studied include: (1) predominant clay mineralogy (kaolinitic, illitic and smectitic); (2) soil texture (4-6 typical textural classes from sandy to heavy clay); and (3) organic matter content (e.g. tillage and or management contribution). Extrinsic conditions that were evaluated include: (1) 4-5 levels of rain kinetic energy (KE, 0-22 kJ/m3); (2) 3-4 wetting rates (WR) of dry soil by rainfall and irrigation water; (3) water quality (rain, fresh, waste or saline water); (4) 4-8 antecedent moisture contents (from dry to full saturation) combined with different aging (timing) durations between consecutive wettings; (5) tillage intensity (conventional and minimum-tillage); and (6) soil sodicity, and use of soil amendments (polymer, gypsum). A multifactor analysis of variance (ANOVA) procedure was performed (SAS Institute 1995) to compare the effect of treatments or factors and their interactions on runoff and erosion. Treatment mean comparisons were made by employing the Tukey-Kramer HSD test using a significance level of 0.05 (SAS Institute 1995).

Results and Discussion

Predominant clay mineraolgy

The main cause for the decrease in soil infiltration under rainfall conditions in arid and semi-arid regions is seal formation at the soil surface. Clay mineralogy was recognized as a dominant factor in controlling soil structure stability, hydraulic properties, and hence formation of seal, runoff generation and erosion (Stern et al., 1991; Lado and Ben Hur, 2004, Reichert et al., 2009; Mamedov et al., 2010). Studies using South African and Israeli soils showed that loss of sediments from predominant smectitic soils was up to ten times higher than from predominant kaolinitinc soils, not containing smectite (Fig. 1). Soil clay mineralogy affects the physicochemical dispersion of the clay and the physical disintegration of soil aggregates, which is greater in soils with a smectitic clay mineralogy with a greater sensitivity to dispersion and aggregate breakdown during wetting. Kaolinitic and illitic soils which do not contain smectite are stable soils, and their structural stability is controlled mainly by stabilizing agents such as organic matter or oxides (Fig. 2). However, results of the susceptibility of numerous phyllosilicate soils to runoff and interrill erosion showed that kaolinitic and illitic soils that contain some smectitic impurities could be more susceptible to seal formation, but still more stable than smectitic soils (Lado and Ben-Hur, 2004; Norton et al., 2006). Based on clay mineralogy, soil ranking with respect to their sensitivity to runoff generation and erosion is in the following order: smectitic > illitic> kaolinitic soils (Figs. 1 and 2).

Soil texture and wetting condition

The combined effects of soil texture and the rate of wetting (WR, 2 -64 mm h^{-1}) of the soil prior to exposing it to rainfall on soil erosion from five typical Israeli semi-arid smectitic soils exhibiting a wide range of clay content (8-60%) is presented in Figure 3. Soil loss and total runoff seem to depend on soil clay content and wetting conditions (Levy et al., 1997; Mamedov et al., 2001; Levy and Mamedov, 2002). The soils with intermediate clay content (20-40% clay) were the most susceptible to soil loss (Fig. 3). The WR had a marked effect on runoff and soil loss, showing that the use of slow WR (e.g. simulation of drip irrigation, residue cover) prevents aggregate slaking and decreases runoff and erosion considerable in soils exposed to high KE rain. The effect of WR on runoff and soil loss increased noticeably with the increase in clay (>40%) content (Figs. 3 and 4).

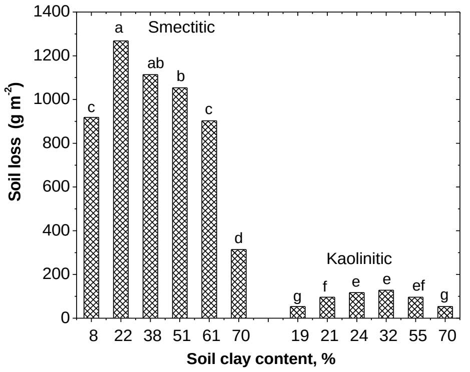

Fig. 1. Clay mineralogy effects on soil loss (from Stern et al, 1991 and Mamedov et al., 2002). Bars labeled with the same letter are not significantly different at P < 0.05 level.

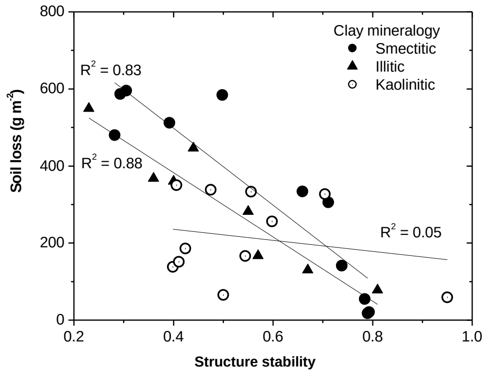

Fig. 2. Soil loss vs. structure stability for soils with different clay mineralogy (from Norton et al., 2006)

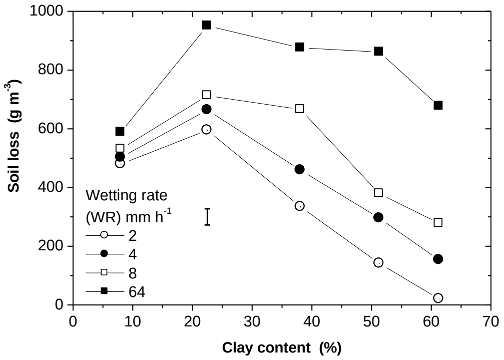

Fig. 3. Soil loss as affected by clay content and wetting rate (from Mamedov et al., 2001). The bar indicates single confidence interval at P<0.05

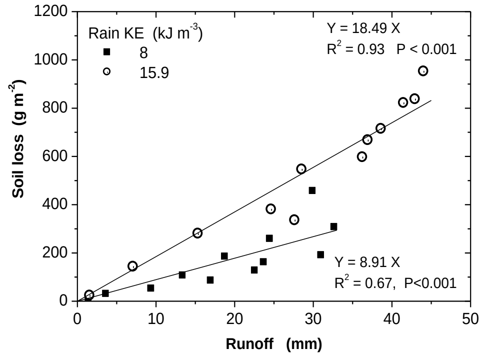

Fig. 4. Relationship between soil loss and runoff for two rain kinetic energy levels (Shainberg et al., 2003).

The relationship between soil loss and runoff could be described by the linear function, which indicates that most of the eroded soil was generated and transported by runoff water (Fig. 4). The observed enrichment of the eroded material by clay-size particles relative to the parent soil material and its dependence on WR and hence on the degree of aggregate slaking under rainfall (Warrington et al., 2009), emphasizes the importance of protecting surface soil aggregates from breaking down during rainstorms (minimum tillage, residue material, etc.), as well as stresses the hazard of eroded sediments serving as a potential source of pollution, degrading water quality in river systems and contaminating downstream areas (Levy et al., 1997; Mamedov et al., 2001; Shainberg et al, 2003; Smith et al., 2005). It should however be noted that, unlike smectitic soils, for predominantly kaolinitic soils the effects of soil texture and wetting condition on soil structure and hence soil loss were not consistent (Norton et al., 2006; Mamedov et al., 2010).

Rain kinetic energy

The effects of rain kinetic energy (KE) on runoff and interrill erosion from four cultivated Israeli soils are presented in Figures 5 and 6. For all the soils, runoff and interrill erosion increased with an increase in rain KE (Mamedov et al., 2000), however the shape of runoff (logarithmic) and soil loss (exponential) curves were different (Figs. 5 and 6). Changes in rain KE led to changes in runoff mainly in the low to moderate rain KE range (< 8 kJ m^{-3}), whereas for interrill erosion this change took place in the medium to high rain KE range (>12 kJ m^{-3}). This phenomena highlights the intricate relationship between runoff and soil loss, and suggests that seal formation was already completed at medium rain KE and therefore the contribution of runoff in facilitating transport for the entrained material is only secondary to the role of soil detachment in determining soil loss (Mamedov et al., 2000). The contribution of rain KE and WR on runoff and soil loss depended on clay content. In the coarse textured soils (e.g. loam) the effect of rain KE was significant, and the effect of WR was small. Conversely, in the fine textured soils (e.g. clay) the effect of WR on was significant and the effect of rain KE was negligible (Figs. 3-6).

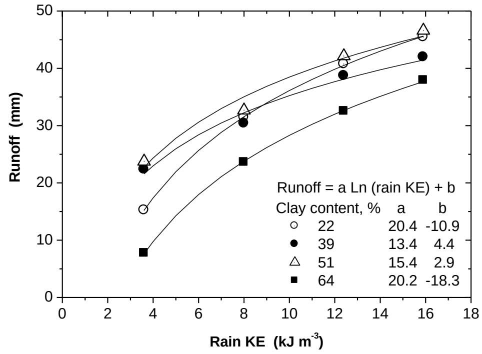

Fig. 5. Runoff as a function of rain kinetic energy and soil texture (Mamedov et al., 2000)

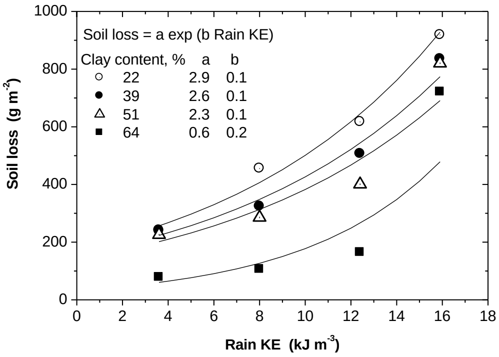

Fig. 6. Soil loss as a function of rain kinetic energy and soil texture (Mamedov et al., 2000)

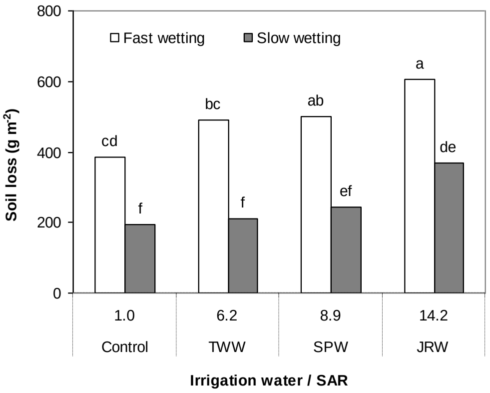

Fig. 7. Total soil loss for the different water quality (SAR) treatments: TWW, treated wastewater; SPW, spring water; JRW, Jordan River water. Bars labeled with the same letter are not significantly different at $P < 0.05$ level (from Mandal et al., 2008).

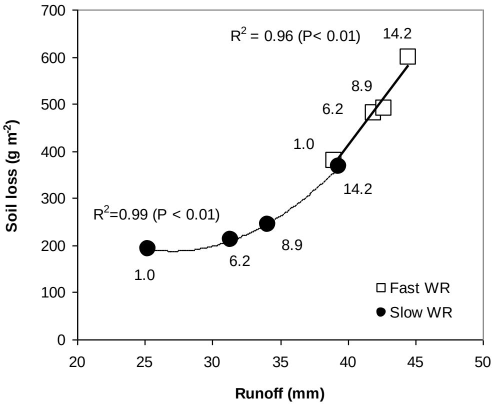

Fig. 8. Total soil loss as a function of total runoff for two wetting condition. Numbers next to plotted points indicate the SAR relevant to the irrigation water (from Mandal et al., 2008).

Water quality

Effects of irrigation water quality on silty clay soil loss (Fig. 7) were tested on a irrigated with either treated waste water (TWW), saline–sodic Jordan River water (JRW), or moderately saline–sodic spring water (SPW). Irrigation with TWW had a consistently more favorable effect on runoff and soil loss than irrigation with the saline–sodic JRW and SPW water (Fig. 7). The results suggest that replacing saline–sodic irrigation water by TWW, with significantly lower salinity and sodicity levels, may prove beneficial in improving soil structural stability and could also mitigate problems associated with high levels of runoff and soil erosion, particularly in regions of low to moderate rainfall intensities (Mandal et al., 2008). For fast wetted samples, the linear relation between erosion and runoff, suggests that erosion is most likely limited by the carrying capacity of the runoff water (Mamedov et al., 2002). Conversely when slow wetting is used and little or no aggregate slaking occurs, the amount of available smaller sized erodible soil material is limited, soil susceptibility to detachment by raindrop impact and runoff flow becomes greater in an exponential manner with the increase in irrigation water SAR or soil sodicity (Fig.8).

Tillage (organic matter)

Effects of tillage intensity on soil loss (conventional tillage [CT] in field crop and no-till [NT] in field crop or minimum tillage [NT] in orchards irrigated with fresh and treated effluent) are presented in Figures 9 and 10. Organic matter content was notable higher in the NT soils than the CT soils. Infiltration rate always were higher under NT than CT soil and the effect was more substantial in soils with high cay content (Fig. 11). Consequently, runoff and soil loss levels under NT were significantly lower than those under CT irrespective of irrigation water quality (Figs. 9 and 10). Moreover soil loss was similar for soils irrigated with fresh water and treated effluent in the NT samples taken from the orchard, thus suggesting that reduced tillage improves the structure of soils irrigated with treated effluent too, and enhances soils aggregate resistance to raindrop impact. Conversely for the intensely tilled field crop section (CT), soil loss was greater in the effluent irrigated soil than in the fresh water irrigated one, signifying that tilled soils have greater sensitivity to erosion, particularly under effluent water quality, due to elevated sodicity and dispersity levels in the effluent irrigated soils (Fig. 10).

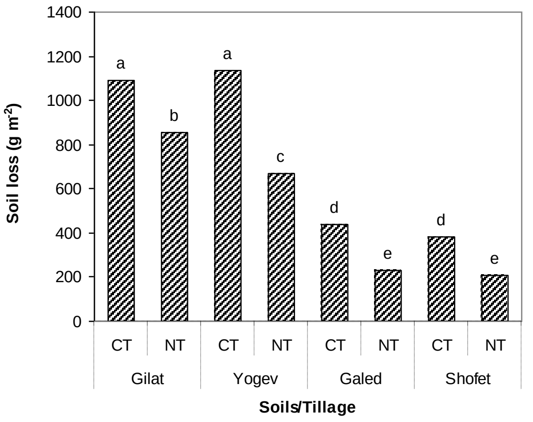

Fig. 9. Effect of tillage intensity on soil loss. Gilat is a loam, and other soils are clay soils. Bars labeled with the same letter are not significantly different at $P < 0.05$ level.

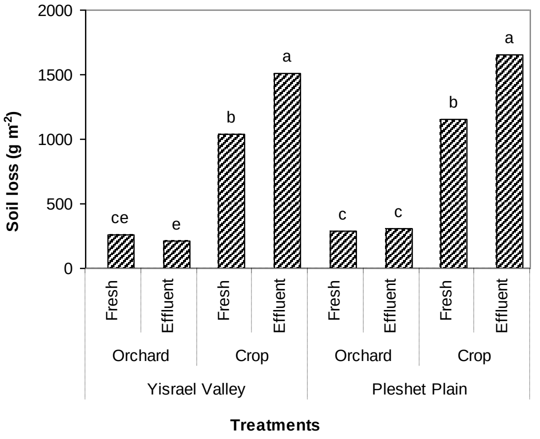

Fig. 10. Soil loss as affected by tillage intensity and water quality for a clay soil (Yisreel valley) and a sandy clay (Pleshet Plain). Bars labeled with the same letter are not significantly different at $P < 0.05$ level

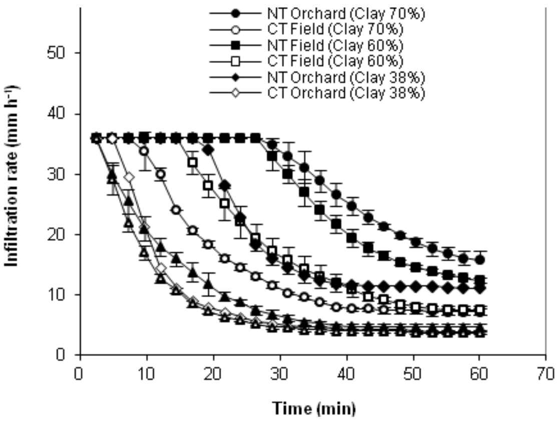

Fig. 11. Infiltration rate as affected by tillage type. Mizra is clay and Shofet is clayey soils and Gilat is a loam. Bar indicate one standard error.

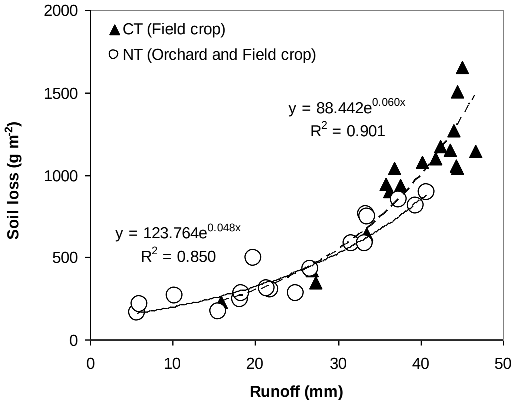

Fig. 12. Soil loss as a function of runoff for intensive tillage (CT) and minimum tillage (NT).

The relationship between soil loss and runoff for both types of tillage were exponential with considerable higher range of runoff and soil loss in CT soils (Fig. 12), showing that under our experimental conditions where mostly stable clay soils were used (i) a similar mechanism but with different intensity (exponent) was operating for both tillage, and (ii) aggregate breakdown by irrigation water, detachment and transport by the rain impact is diminished, but carrying capacity of the runoff was not the limiting factor for soil loss, particularly under NT condition for both water quality and cropping. For course textured soils effect of NT was a less evident. Soil structure stability and thus erosion do not only depend on soil texture and organic matter content, but also on the conditions that prevail in the field. Intensive cultivation escalated runoff and soil loss (Figs. 9-12) because it causes a periodical mechanical disruption of soil aggregates, a deterioration in soil structure an increase in the rate of soil organic matter decomposition and affects microbial activity (Norton et al., 2006) all of which result in greater amounts of dispersed clay, i.e. making the soil more susceptible to raindrop impact and erosion.

Antecedent moisture content and aging

The combined effects of two different surface conditions, i.e., antecedent moisture content (AMC) and aging duration, on runoff and erosion from 4 smectitc Israeli soils are presented in Figures 13 and 14. The results reveal the existence of an optimal range of AMC (matric potential, pF =2.4-4.2, between wilting point and field capacity) at which runoff and erosion levels are lower by up to 30%, than those obtained at AMC levels above or below the optimal range. Increasing aging (e.g. time between wetting the soil) duration (from 0 day to 7 ay) resulted in a 15-30% decrease in runoff and soil loss at this optimal AMC range in comparison to no aging; effects of aging at optimal AMC on runoff and soil loss were of greater magnitude in clay soils (Figs. 13 and 14). A similar manner at which runoff and soil loss decreased with the increase in aging duration at the optimal AMC range was noted, thus indicating that, for the given experimental conditions, runoff was the main precursor for soil loss (Levy et al., 1997; Mamedov et al., 2006). The combined favorable impact of AMC and aging on improving soil stability was associated with water-filled pores that were of the size range belonging to the clay fabric. Clay movement and reorientation have, therefore, been considered as key factors in the development of cohesive forces between and within soil particles during aging at optimal AMC levels (Mamedov et al., 2006).

Sodicity

The combined effects of sodicity (ESP 2-20) and soil texture (loamy sand to heavy clay) on erosion of 24 cultivated Israeli soils are presented in Figure 15. Soil loss increased with the increase in sodicity (ESP) with the magnitude of the effects depending on clay content (Fig.15). An exponential type relation between erosion and runoff was observed (Fig.16), whereas for non sodic soils (ESP<2) this relationship was linear (Fig. 4). Increase of sodicity (from ESP 2 to ESP 20) increased the physico-chemical clay dispersion and weakens aggregates and therefore increases runoff and soil loss by more than 2-4 times. Under high KE rain and fast wetting the surface aggregates are exposed to both types of force (i.e., slaking by wetting and detachment by high raindrop impact and by the subsequently formed runoff). Thus, the noted exponential relationship (Fig. 16) was ascribed in the sodic soils to high volume and velocity of runoff water that can initiate rill erosion which supplements detachment by raindrops in markedly increasing erosion (Levy et al., 1994; Mamedov et al., 2002).

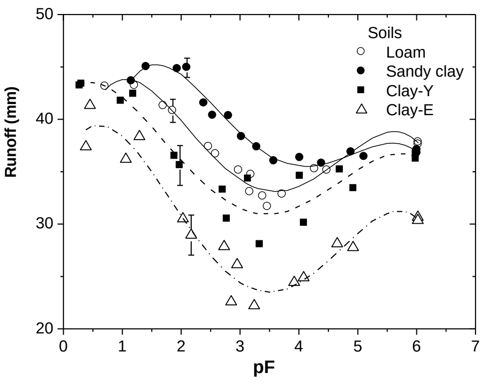

Fig. 13. Effect of antecedent moisture content (pF) on runoff in 3-7 day aging duration. The bar indicate single confidence interval (from Mamedov et al., 2006).

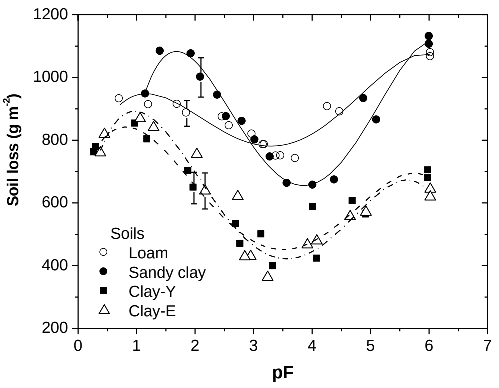

Fig. 14. Effect of antecedent moisture content (pF) on soil loss in 3-7 day aging duration. The bar indicate single confidence interval (from Mamedov et al., 2006).

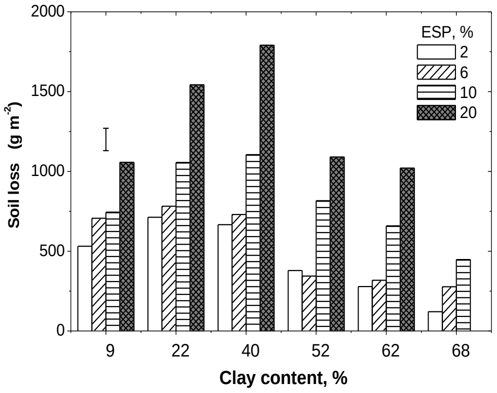

Fig. 15. Soil loss as affected by soil sodicity for a range of soil texture (from Mamedov et al., 2002). Bar indicate single confidential interval.

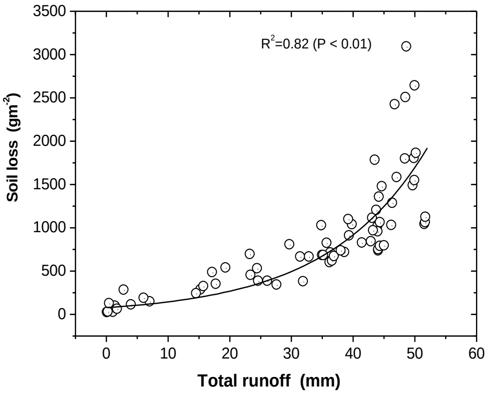

Fig. 16. Soil loss as a function of runoff (from Mamedov et al., 2002) for a range of soil texture and four sodicity level (see Figure 15).

Amendments

The effects of surface application of two anionic polyacrylamides (PAMs), varying in their molecular weight (MW, moderate-M and high-H), in combination with posphogypsum (PG), on seal formation, runoff, and soil erosion in 5 Israeli smectitic soils varying in texture was studied by Mamedov et al. (2009). The two PAMs maintained runoff and soil loss levels that were lower, than those obtained in either the control or PG alone treatments (Figs. 17 and 18). Both PAMs, mixed with PG, increased soil structure stability and hence final IR by 3 to 5 times (data not presented) and reduced runoff and erosion by 2 to 4 times relative to the control (Fig. 17). However, PAM (M) treatments yielded lower levels of runoff and soil erosion compared with the PAM (H) one, that were ascribed to its lower viscosity when in solution. Effect of soil amendments on soil erosion were more notable in course texture soils (Fig.17), whereas an effect of wetting condition were considerable higher in fine textured soils (Fig.3), showing that in soils with <40% clay, prevention of physicochemical clay dispersion (e.g., by gypsum application) is preferable for controlling soil erosion, whereas in clay soils, prevention of aggregate slaking during the wetting process of the soil emerged as a more beneficial management (Figs.3 and 17).

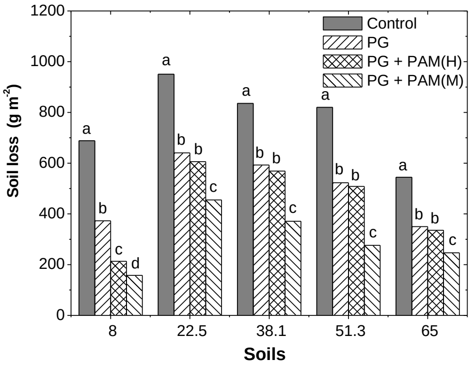

Fig. 17. Total soil loss as a function of the treatments for the 5 soils. Within a soil type, bars labelled with the same letter are not significantly different at $P < 0.05$ level. Control; PG, phosphogypsum (4 Mg/ha); PAM(H) and PAM(M) polyacrylamide with high and moderate molecular weight (20 kg/ha) respectively, (from Mamedov et al., 2009)

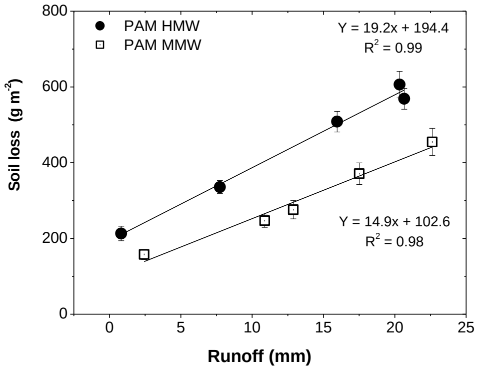

Fig. 18. Total soil loss as a function of cumulative runoff for the soils treated with 2 types of PAM. PAM(H), polyacrylamide with high molecular weight (20 kg/ha); PAM(M), polyacrylamide with moderate molecular weight (20 kg/ha); each PAM was mixed with PG, phosphogypsum (4 Mg/ha); Bars indicate 1 standard error (from Mamedov et al., 2009).

Conclusion

Cultivated fields exhibit usually a complex spatio-temporal variability of soil characteristics, i.e. soil properties and conditions (affected by management, irrigation and rain water regime or characteristics, etc.). Our review of published literature suggests that factors and mechanisms controlling upslope soil erosion are complex and depend on various processes. Generally, runoff generation and soil erosion increased exponentially with the increase in rain KE and soil WR. Rain KE and water quality played a predominate role in determining soil loss in medium- and coarse-textured soils (2-40% clay), while WR played a predominate role in fine-textured soils (40-70% clay). Soils from semi-arid regions, particularly clay soils, having moisture content in the range between wilting point and field capacity (pF 2.7-4.2), generate low levels of runoff and sediments. In soils with <20-40% clay, prevention of physicochemical clay dispersion (e.g., by gypsum and PAM application) is preferable for controlling soil erosion, whereas in clay soils, prevention of aggregate slaking during the wetting process of the soil could be more beneficial. Application of a small amount of polymer in combination with gypsum may effectively decrease soil loss by to 2-4 times relative to the control, mostly in smectitic soils.

The reviewed results indicate that effects of WR on soil loss depended on soil clay content and mineralogy, thus making the task of predicting soil susceptibility to erosion even more complicated. Most erosion models consider only soil inherent properties (mainly texture) in the computation process of soil erosion. To improve the prediction capabilities of models (such us WEPP), soil type and conditions before erosive rainstorms such as clay mineralogy, AMC, wetting should be considered and incorporated in process-based erosion models. Though inherent soil properties cannot be changed, conditions prevailing in the soil can be manipulated by changing management practices (e.g., tillage intensity, irrigation water quality, use of amendments and plant residue materials, manipulation of soil moisture level, etc.,) to reach at conditions that decrease soil susceptibility to soil erosion. Our results can assist in understanding the changes in the degree of erosion, sediment and chemical transport, and thus potential water quality concerns in soils and could be useful for modeling efforts aimed at the prediction of soil erodibility.

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