Published online March 29, 2006

Reproduced from Soil Science Society of America Journal. Published by Soil Science Society of America. All copyrights reserved.

Antecedent Moisture Content and Aging Duration Effects on Seal Formation and Erosion in Smectitic Soils

A. I. Mamedov,* C. Huang, and G. J. Levy

ABSTRACT

Soil susceptibility to seal formation and erosion depends on its inherent properties and surface conditions. Our objective was to study the interaction of two different surface conditions, antecedent moisture content (AMC) and aging duration, on seal formation and erosion in four smectitic soils. Soil samples were packed in trays and wetted with different amounts of water (0, 1, 2, 3, 4, 6, 8, or 16 mm) with a mist type rain. The wetted samples were put in plastic bags and allowed to age for 0.01, 1, 3, or 7 d. The soil trays were exposed to 60 mm of distilled water rain of high energy. At no aging (0.01 d), runoff volume (a measure for seal development) and soil loss increased with an increase in AMC mainly because of enhanced slaking. In general, runoff and soil loss decreased with the increase in aging duration. For instance, in the Clay (Y) soil, to which 3 mm of water was added, as aging increased from 1 to 7 d, runoff decreased from 39 to 28 mm, and soil loss decreased from 660 to 397 g m^2. For any given aging duration, the smallest runoff volume and soil loss were obtained at the intermediate AMC levels (2, 3, and 4 mm of water added); at this AMC range, increasing aging time resulted in up to 40% decrease in runoff or soil loss. The effects of aging at these AMC levels (generally between wilting point and field capacity [i.e., pF 4.1–2.4]) were significantly more pronounced for clay soils probably because at these AMCs water-filled pores in the clay fabric were considered active in the stabilization process and the development of cohesive bonds between and within particles during the aging period. Soil erosion changed with the increase in aging duration in a manner similar to runoff, suggesting that runoff was the main precursor to erosion under these conditions.

Surface sealing, runoff, and soil erosion occur when soil surfaces are exposed to the beating action of rain drops. Seal formation is caused by two complementary mechanisms: (i) a physical breakdown of soil aggregates caused by the mechanical impact of water drops and (ii) a physicochemical dispersion and movement of clay particles into the 0.1- to 0.5-mm soil surface layer, where they lodge and clog the conducting pores (McIntyre, 1958; Agassi et al., 1981). The latter mechanism is controlled mainly by the concentration and composition of the cations in the soil and applied water (Agassi et al., 1981; Kazman et al., 1983; Shainberg and Levy, 1992) and by clay content (Ben-Hur et al., 1985, Mamedov et al., 2001). The role of physical breakdown of surface aggregates (first mechanism) in the sealing process is complicated and depends on rain properties (intensity and energy) and the stability of the aggregates (Betzalel et al., 1995; Shainberg et al., 2003; Levy and Mamedov, 2002).

Aggregate stability has commonly been associated with various soil properties (e.g., organic matter, clay percentage, and oxides content), which contribute to the binding processes in the soil (Kemper and Koch, 1966; Goldberg et al., 1988; Levy and Mamedov, 2002). However, aggregate stability depends also on conditions prevailing in the soil, such as antecedent moisture content (AMC) of the aggregates, the rate at which the aggregates have been wetted, and aging duration (i.e., the period of time the aggregates were left undisturbed at a given moisture content) (Panabokke and Quirk, 1957; Francis and Cruse, 1983; Kemper and Rosenau, 1984; Truman et al., 1990; Loch, 1994; Kjaergaard et al., 2004). Wetting and keeping the soil at a given moisture content (i.e., aging) induces an increase in aggregate strength through the development of cohesive bonds between the soil particles (Kemper and Rosenau, 1984; Attou et al., 1998). Prolonged aging seems to have a favorable effect on the development of intra-aggregate cohesion forces (Blake and Gilman, 1970; Utomo and Dexter, 1981). Furthermore, effects of aging on aggregate stability were noted to depend on AMC and soil texture (Gerard, 1965; Utomo and Dexter, 1981). On the other hand, inconsistent findings have been reported regarding the effect AMC per se has on the development of soil cohesion; some studies reported a decrease in soil cohesion with the increase in AMC (Kemper et al., 1987; Kemper and Rosenau, 1984; Kjaergaard et al., 2004), whereas other studies reported the opposite (Truman et al., 1990; Bradford and Huang, 1990).

The dependence of aggregate stability on AMC has been linked to aggregate detachment, soil erosion, and seal formation (Farres, 1987; Bradford et al., 1992; Le Bissonnais, 1996; Levy and Mamedov, 2002). Recently, McDowell and Sharpley (2002) have observed that soil AMC and soil erosion were associated in affecting the potential loss of soil nutrients within catchments areas. Furthermore, moisture content and aging duration interaction have been found to determine aggregate breakdown mechanism, the resulting particle size distribution, and the evolution of the structure of the seal (Kemper and Rosenau, 1984; Le Bissonnais, 1990). Although the role of these time-dependent factors on aggregate stability in relation to seal formation and soil erosion has been studied extensively, the results obtained were

---

A.I. Mamedov and G.J. Levy, Institute of Soil, Water and Environmental Sciences, Agricultural Research Organization (ARO), The Volcani Center, P.O. Box 6, Bet-Dagan 50-250, Israel. A.I. Mamedov is currently at the National Soil Erosion Research Lab., USDA-ARS-MWA, West Lafayette, IN, 47907. C. Huang, National Soil Erosion Research Lab., USDA-ARS-MWA, West Lafayette, IN, 47907. Contributions from the Agricultural Research Organization (ARO), The Volcani Center, P.O. Box 6, Bet-Dagan 50-250, Israel. No. 621/2004. Series. Received 16 Dec. 2004. *Corresponding author (amrakh@purdue.edu).

Published in Soil Sci. Soc. Am. J. 70:832–843 (2006).
Soil & Water Management & Conservation
doi:10.2136/sssaj2004.0391
© Soil Science Society of America
677 S. Segoe Rd., Madison, WI 53711 USA

Abbreviations: AMC, antecedent moisture content.

inconclusive. Luk (1985) reported a fivefold increase in soil loss for loam and silty loam soils on increasing moisture content from wilting point to saturation. The author concluded that increasing AMC may have led to shear strength reduction. Other studies also showed that soil susceptibility to detachment increased as soil moisture content increased (Cruse and Larson, 1977; Al-Durrah and Bradford, 1981; Francis and Cruse, 1983; Le Bissonnais et al., 1995; Froese et al., 1999). A loam with a matric potential between 0 and −0.5 kPa produced 30 times more splash detachment than when the matric potential was between −0.5 and −1.0 kPa (Francis and Cruse, 1983). Froese et al. (1999) observed a similar increase in splash detachment when water potential changed from low (−1045 to −65 Pa) to high (−65 to 0 Pa).

Wangemann et al. (2000) concluded that infiltration rate and aggregate stability decreased in three loam soils as AMC increased from 5 to 20%. By contrast, Le Bissonnais and Singer (1992) obtained for loam and clayey soils (30 and 42% clay content) significantly higher infiltration rates and lower erosion levels for wetted (24 h by a matric potential of 1.0 kPa) soil samples compared with air dry ones. Lado et al. (2004) observed that for fast and slow wetted soil samples, initially wet soils had lower soil loss than an air-dry soil. Truman and Bradford (1990) noted that wetting of soil (five soils with clay content 11–53%) gradually for 48 h reduced splash and wash erosion significantly compared with air-dried soil but had no significant effect on total runoff values. Reichert and Norton (1994) also reported that pre-wetting 12 dry mostly clay soils (10 clay and two loam) for 2 h at −0.54 kPa generally had a little effect on runoff and soil loss except for a stable clay Oxisol. Moreover, in this study the increased aggregate stability observed with capillary pre-wetting was not accompanied by an increase in infiltration. Farres (1987) noted that total splash loss from 20 soils with different clay content was not a linear function of individual aggregate stability. Farres (1987) also observed that the higher the clay and coarse sand contents, the lower the aggregate stability. Bradford et al. (1987) studied the effect of wetting (48 h by a 0 matric potential) on surface sealing for 20 soils ranging in texture from sand to clay and noted no significant relationship between percent of water stable aggregates and infiltration rate (IR) or splash erosion. On the other hand, Bradford and Huang (1990) reported that the effect of AMC on seal formation depended on soil texture; in clay soils wetting increased the final IR and decreased soil loss compared with air-dried soils, whereas in loam soils the opposite was found.

Levy et al. (1997) proposed that the conflicting effects of AMC on aggregate breakdown and detachment, seal formation, and soil loss could be explained by separating these effects into effects of wetting rate and aging. It was suggested that (i) slow wetting increases aggregate stability and reduces slaking and susceptibility to sealing and erosion and (ii) prolonged aging enhances the cohesive forces between soil particles and decreases their tendency to form a seal (Levy et al., 1997). Soil texture, particularly clay content, was also found to be a controlling factor in the AMC effect (Shainberg et al., 1996).

Because most of the prior studies on AMC effects did not consider or controlled the rate of wetting and the compounding effect of aging, the results in seal formation and erosion studies varied, and no clear conclusions could be derived. This inconsistency can also be attributed to considerable differences in soil texture, methods used for aggregate stability, and seal formation measurements (Reichert and Norton, 1994; Le Bissonais, 1996; Levy and Mamedov, 2002). The objectives of this study were to determine in a systematic way the effects of AMC and aging duration on seal formation, runoff, and soil loss in four soils varying in texture.

MATERIALS AND METHODS

Soils

Four smectitic calcareous soils (Banin and Amiel, 1970), representing the main arable soils in Israel, were chosen for this study. The soils were a loam (Calcic Haploxeralf) from the northern Negev, a sandy clay (Chromic Haploxerert) from Hafetz Haim in the Pleshet Plains, and two clays (Chromic Haploxerert) from Yagur in the Zevulun Valley (Clay Y) and Eilon in the Western Galilee (Clay E). Samples from the cultivated layer (0–250 mm) of each soil type were brought to the laboratory. Selected physical and chemical properties of the soils, determined by standard analytical methods (Klute, 1986; Page et al., 1986), are presented in Table 1.

Infiltration, Runoff, and Erosion Measurements

Infiltration, runoff, and erosion were investigated using a drip type rainfall simulator. The simulator consisted of a 750× 600×80-mm closed chamber that generated rainfall of a known constant drop size through a set of hypodermic needles (~1000) arranged at spacing of 20 × 20 mm. The average droplet diameter was 2.97 ± 0.05 mm. Kinetic energy of the rain was maintained at 15.9 kJ m^{-3} by placing the rain simulator at 2.2 m above the soil trays. The impact velocity of the drops was 5.64 m s^{-1} (Epema and Riezebos, 1983). Rain intensity was maintained at 36 mm h^{-1} using a peristaltic pump.

Air-dried soil aggregates, crushed to pass through a 4.0-mm sieve, were packed in 200×400-mm trays, 40 mm deep, over a 20-mm–thick layer of coarse sand to a bulk density of 1.31,

Table 1. Physical and chemical properties of soils studied (mean ± standard error, *n* = 3).

Soil	Soil type	Particle-size distribution sand silt clay			$CaCO_3$	CEC†	ESP	OM %	Bulk density (*n* = 96)
		g kg^{-1}			%	c mol_c kg^{-1}	%		g cm^{-3}
Loam	Calcic Haploxeralf	413 ± 10.22	362 ± 10.16	225 ± 8.54	18.2 ± 0.41	17.7 ± 0.17	2.1 ± 0.08	1.22 ± 0.12	1.31 ± 0.01
Sandy clay	Chromic Haploxerert	465 ± 6.87	154 ± 3.87	381 ± 7.85	9.6 ± 0.23	34.8 ± 0.19	1.6 ± 0.07	1.10 ± 0.04	1.27 ± 0.01
Clay (Y)	Typic Haploxerert	145 ± 3.58	342 ± 5.94	513 ± 7.39	20.2 ± 0.67	57.4 ± 0.44	1.7 ± 0.14	1.76 ± 0.09	1.24 ± 0.01
Clay (E)	Typic Haploxerert	250 ± 3.46	138 ± 5.68	612 ± 6.07	4.9 ± 0.15	65.0 ± 0.26	0.9 ± 0.04	1.68 ± 0.07	1.23 ± 0.01

† CEC, cation exchange capacity; ESP, exchangeable sodium percentage; OM, organic matter.

Reproduced from Soil Science Society of America Journal. Published by Soil Science Society of America. All copyrights reserved.

Reproduced from Soil Science Society of America Journal. Published by Soil Science Society of America. All copyrights reserved.

1.27, 1.24, and 1.23 g cm^{-3} for the loam, sandy clay, Clay (Y), and Clay (E), respectively. After packing, the trays were wetted from above with 0 (air dry), 1, 2, 3, 4, 6, 8, or 16 mm of mist at a rate of 50 mm h^{-1} using tap water (electrical conductivity = 0.9 dS m^{-1}). The diameter of the mist drops was <0.1 mm, maximum drop velocity was ~0.1 m s^{-1}, and the kinetic energy of the drops was <0.01 kJ m^{-3}. Thereafter, each treatment was left to age for 15 min (0.01 d), 1, 3, or 7 d. During aging, the trays were kept in plastic bags to prevent evaporation. Before each rain storm, three replicate samples from depths of 0 to 6, 6 to 13, and 13 to 20 mm of the soil in the tray were taken, and gravimetric soil moisture content was determined. After the predetermined aging duration, the trays were placed in the rainfall simulator at a slope of 15% and exposed to 60 mm of distilled water (electrical conductivity = 0.004 dS m^{-1}) of rain with kinetic energy of <0.01 kJ m^{-3} (mist type rain) or kinetic energy of 15.9 kJ m^{-3}. For the former, only samples that have been left for 0.01 d of aging were tested. During each storm, water infiltrating through the soil was collected for 2 min repeatedly every 4 min in graduated cylinders placed underneath a special outlet at the bottom of the tray, and its volume was recorded as a function of time. Runoff was collected continuously throughout the storm in buckets. At the end of the storm, the buckets were weighed, dried, and weighed again for determination of runoff volume and weight of sediments removed. Three replicates were used for each treatment concurrently. Sixty mm of rain was enough to achieve steady-state IR and runoff in all treatments.

Data Analysis

Infiltration data obtained from the rainfall simulator were analyzed using the nonlinear equation proposed by Morin and Benyamini (1977):

$$I_t = (I_i - I_f)\, e^{-\gamma pt} + I_f \qquad [1]$$

where I_t is instantaneous infiltration rate (mm/h), I_i is initial infiltration rate (mm/h), I_f is final infiltration rate (mm/h), γ is soil coefficient related to surface aggregate stability (1/mm);,t is time from the beginning of the storm (h), and p is rain intensity (mm/h).

A nonlinear regression program used the measured I_t, I_f, and P values to calculate the other two parameters of the equation (I_i and γ) that gave the best coefficient of determination ($r^2 > 0.9$) between paired calculated and measured I_t values.

Volume of runoff (Roff) for any given depth of rain (n) from each single rainstorm was calculated as follows:

$$\text{Roff} = \sum_{j=i}^{n} [d_j - (I_t)_j d_j/p] \qquad [2]$$

where I_t is the calculated instantaneous infiltration rate (from Eq. [1]) for interval number j, p is the rain intensity, and d_j is depth of rain applied during interval number j (d was taken as 1 mm for all intervals). For cases where $(I_t)_j > p$, $(I_t)_j$ was taken as equal to p. For each of the soils studied, the relationship between paired measured, R(m) and predicted, R(p) was linear: In clay soils: R(m) = (0.86–0.91)R(p), in loam R(m) = (0.85–0.88)R(p). In both cases, $R^2 > 0.84$ ($P < 0.05$). There is no "out of tray splash" problem in the field. Therefore, we preferred to use calculated runoff values rather than measured runoff data of water splash from the soil trays that could amount to 15% of the applied rain (Agassi and Levy, 1991).

Moisture content, pF, runoff, and soil loss data were subjected to a analysis of variance (AVOVA) (SAS Institute, 1999). The general linear model and/or mixed linear test model were used for ANOVA and mean separation tests. Bartlett's test of homogeneity was performed for all treatments before ANOVA. In cases where interactions were noted among treatments, differences among pF, runoff, or soil loss of individual treatments were determined using a single confidence interval value at level $P < 0.05$ (SAS Institute, 1999).

RESULTS AND DISCUSSION

Results of the AMC at the upper soil layer (0–0.6 mm) for the different amounts of water added (0–16 mm) and after the different aging periods (0.01–7 day) show that differences in clay content among the soils tested yielded different moisture contents (Fig. 1). In addition, AMC in the upper soil layer decreased with an increase in aging duration. Based on measurements of moisture content in the loam to a depth of 20 mm for 2 and 6 mm of water added (Table 2), it was concluded that the observed changes in AMC were due mostly to further water redistribution in the soil, with more water leaving the upper soil layer and moving deeper into the soil as aging duration increased (Table 2). Water loss to evaporation was considered insignificant because the soil trays were stored in plastic bags when left for the different aging periods. Thus, as a result, exact comparison of the effects of aging duration on a given parameter (i.e., runoff or soil loss) at a chosen level of water added was difficult because of the change in AMC over different aging periods (Fig. 1). Furthermore, because of the differences in texture among the soils tested, it was deemed important to consider the effects of water in the soil in terms of water status (matric potential) in addition to moisture content. For each soil, we calculated the matric potentials for the corresponding measured moisture content levels using the water retention characteristics of the given soil that had been determined by Gupta et al. (1990). The calculated matric potential were presented as pF values (i.e., the logarithm of the negative of the water potential expressed as cm of H_2O) (Schofield, 1935) and are shown in Fig. 2.

Bartlett's test (SAS Institute, 1999) was used to support assumptions made about the homogeneity of the variance of the moisture content or pF (matric potential) data for each soil (Fig. 1 and 2). Results of Bartlett's test showed that variance was homogenous across all treatments. For each soil an ANOVA showed a significant interaction between the amount of water added and aging time on the moisture content and pF at a layer 0 to 6 mm (Table 3). A single confidence interval value (SAS Institute, 1999) was used to identify significant differences among individual treatments (Fig. 1 and 2). The following discussion focuses, therefore, on the effects of AMC and/or pF at each individual aging duration.

Effects of Antecedent Moisture Content and Aging

Soil susceptibility to seal formation is often characterized quantitatively by changes in its infiltration rate and/or runoff rate with time or by cumulative rain. Infiltration curves per se are not suitable for quantitative

Reproduced from Soil Science Society of America Journal. Published by Soil Science Society of America. All copyrights reserved.

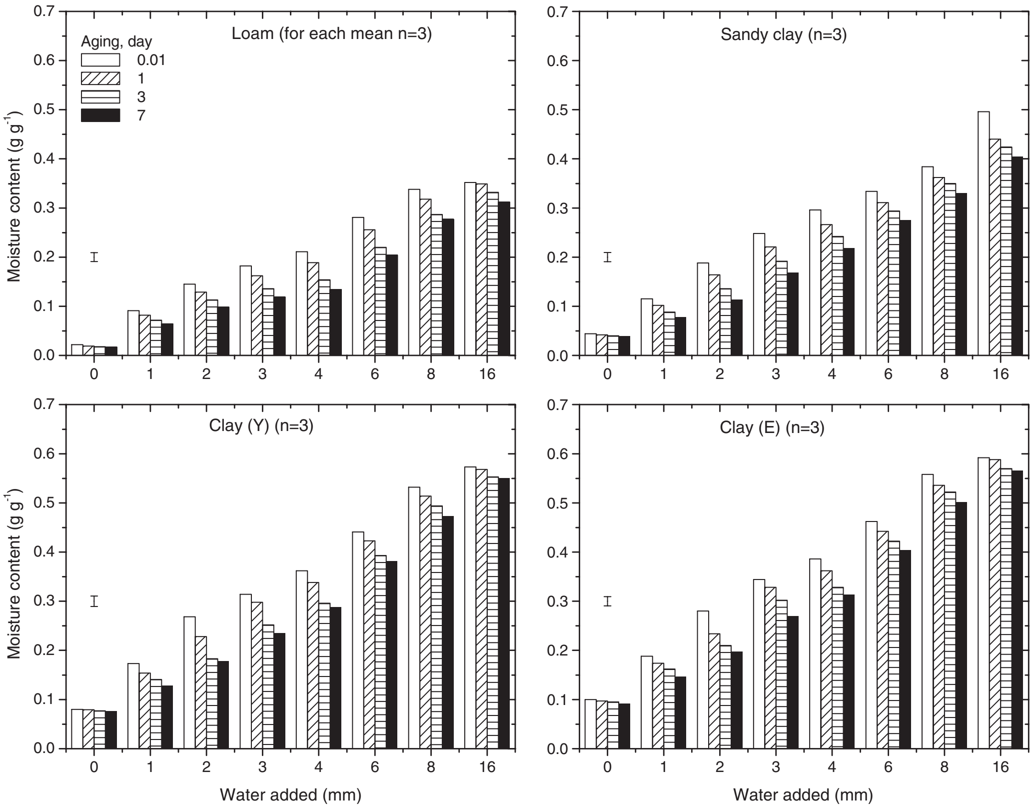

Fig. 1. Moisture content at the upper 6 mm of the soil samples as a function of the amount of water added and aging duration. For each soil, the bar indicates a single confidence interval at $P < 0.05$.

comparison among treatments. Runoff volume represents the degree of seal development and is also an integrated value that depends mainly on the rate at which the seal is formed. In the current study we opted, therefore, to use total amount of runoff from the entire rain event.

In the study with rain of very low energy (i.e., mist type rain), the infiltration curves were all a flat line (parallel to the *x* axis) that almost equaled the rain intensity used (36 mm h^{-1}). The amounts of runoff and soil loss obtained in the mist type of rain experiments were 20 to 35 (runoff) and 60 to 100 (soil loss) times less than those obtained at the optimum AMC content, which exhibited minimum runoff and soil loss values. Thus, the following discussion focuses only on results obtained from rain with energy.

Calculated runoff and measured soil loss values from the 60 mm rain with high-energy storms for given aging duration and different levels of water added and soil types are presented in Fig. 3 and 4. For each soil and aging period, differences among runoff (Fig. 3) and soil loss (Fig. 4) data for the different amounts of water added were determined using the Tukey's HSD test (SAS Institute, 1999). When the soils were not allowed to age, runoff tended to increase or remained constant as the amount of water added during wetting increased (i.e., increase in moisture content) in all four soils (Fig. 3). In this case the main mechanisms responsible for governing surface sealing and runoff were (i) slaking of surface aggregates due to the fast wetting rate (50 mm h^{-1}) (Mamedov et al., 2001) at which the predetermined water amounts were added to the soil, and (ii) the impact of the raindrops (Shainberg et al., 2003). With the increase in the amount of water added, more surface aggregates had the opportunity to slake and therefore the soil was more susceptible to seal formation; consequently, for all soils, larger volumes of runoff (31–43 mm) and soil loss (600–1200 g m^{-2}) were observed (Fig. 3).

When the soils were allowed to age, the smallest amounts of runoff (22–36 mm) and soil loss (360–790 g m^{-2}) were obtained for the intermediate volumes of water added (i.e., 2–4 mm of water) (Fig. 3–5), corresponding to pF values, generally in the range of 4.1 to 2.4 for the studied soils (see Fig. 2). This observation became more noticeable with the increase in aging duration (3–7 d), at pF values in the range of 2.7 to 4.1 (3.7–2.9, 4.3–2.8, 4.2–2.7, and 4.1–2.7 for the loam, sandy clay, Clay [Y] and Clay [E], respectively) with a maximum

Table 2. Distribution of water in soil profile of loam soil (mean ± standard error, $n = 9$).

Water added	Soil depth	Moisture content, g g^{-1}		
mm	mm	Aging, day		
		0.01	1	7
2	6	0.144 ± 0.007	0.129 ± 0.009	0.098 ± 0.006
	12	0.138 ± 0.008	0.146 ± 0.006	0.136 ± 0.004
	20	0.115 ± 0.005	0.118 ± 0.004	0.124 ± 0.002
6	6	0.281 ± 0.007	0.256 ± 0.006	0.204 ± 0.010
	12	0.241 ± 0.011	0.284 ± 0.006	0.258 ± 0.006
	20	0.205 ± 0.005	0.193 ± 0.008	0.221 ± 0.009

Reproduced from Soil Science Society of America Journal. Published by Soil Science Society of America. All copyrights reserved.

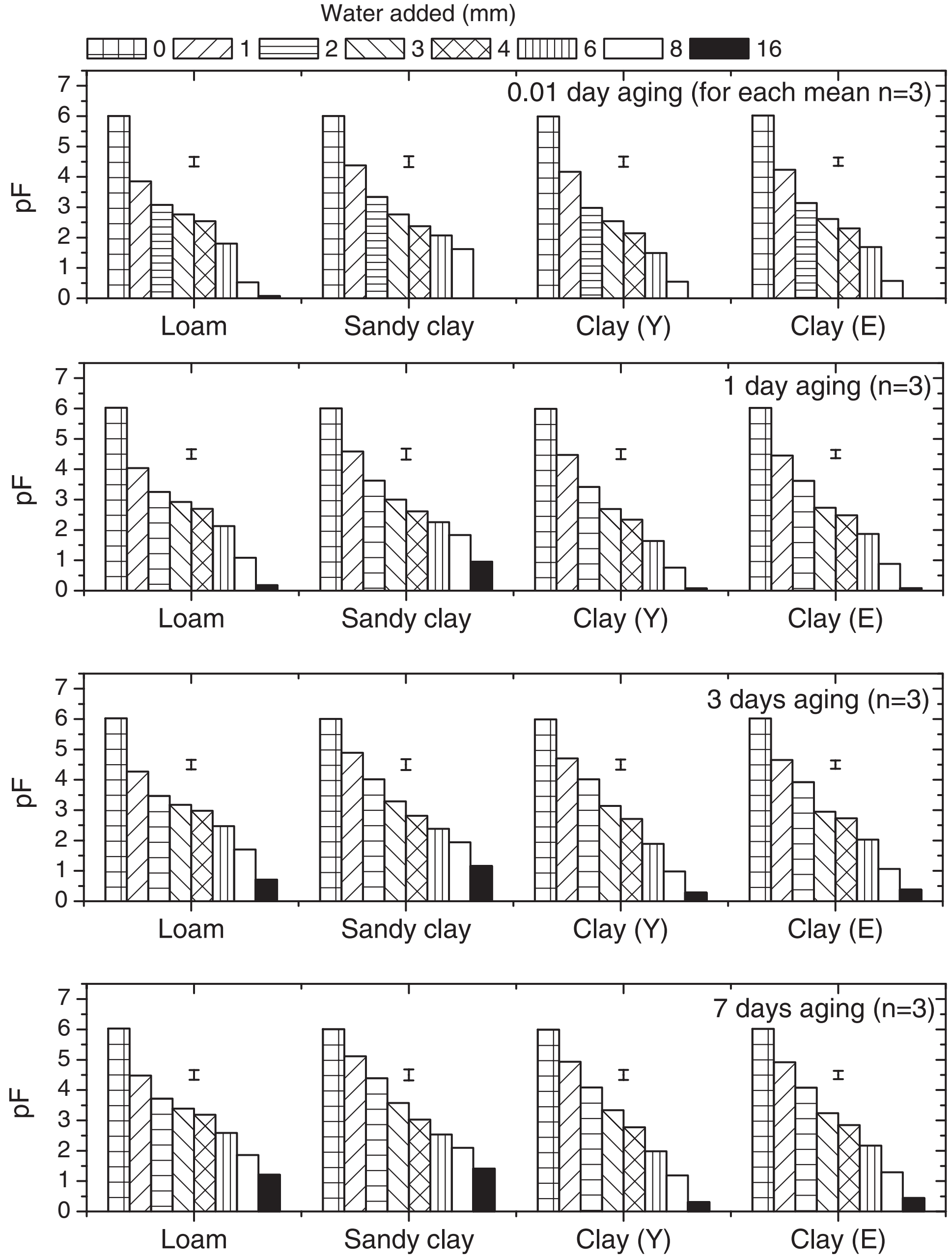

Fig. 2. Matric potential, expressed in pF units, at the upper 6 mm of the soil samples as a function of aging duration and the amount of water added. For each soil at a given aging duration, the bar indicates a single confidence interval at $P < 0.05$.

effect at pF ~3.5 for all soils (Fig. 5). At pF ~3.5 and prolonged aging (7 d) runoff was 33, 35, 28, and 22 mm and soil loss was 740, 620, 400, and 360 g m^{-2} for the loam, sandy clay, Clay (Y), and Clay (E), respectively (Fig. 3–5). This observation suggested that the level of AMC in the soil played a significant role in determining the beneficial effects of aging on stabilizing aggregates and soil structure and improving soil resistance to sealing and erosion. Furthermore, it indicated the existence of a range of AMC below and above which the soil becomes more sensitive to breakdown and seal formation. A more narrow range of pF was reported by Blake and Gilman (1970) who stressed that the relative high stabilities of artificially prepared aggregates from a silty and a sandy loam after 1 to 3 d of aging, were at intermediate water contents (pF values of 3.3–2.8). Conversely, Gernuda et al. (1954), who examined the effect of AMC on aggregate slaking, did not observe an optimum AMC above and below which slaking of aggregates was enhanced.

Shainberg et al. (1996) also noted that the increase in soil stability via aging required an optimal AMC and suggested that aging allows the development of inter- and intra-particle cohesive forces that stabilize not only aggregates but also soil structure. It had been hypothesized that cohesion forces were associated with (i) capillary water (Kemper and Rosenau, 1984) and (ii) clay movement and reorientation (Shainberg et al., 1996;

Reproduced from Soil Science Society of America Journal. Published by Soil Science Society of America. All copyrights reserved.

Table 3. Significance of effect of the amount of water added and aging duration on (a) moisture content and (b) pF for each soil.

Soil	Source of variation	df	Sum of squares	F-ratio	Significance	SCI†	Sum of squares	F-ratio	Significance	SCI
			(a) Moisture content (g g^{-1})				(b) pF			
Loam	Water added (WA)	7	1.01	1157.16	***		245.76	581.05	***	
	Aging	3	0.04	93.93	***		7.08	39.05	***	
	WA*Aging	21	0.01	3.31	***	0.009	2.76	2.18	**	0.16
	Error	64	0.01				3.87			
	Corrected total	95	1.06				259.47			
Sandy clay	Water added (WA)	7	1.52	1718.98	***		226.48	640.90	***	
	Aging	3	0.05	124.24	***		6.43	42.46	***	
	WA*Aging	21	0.01	3.68	***	0.009	2.33	2.20	**	0.15
	Error	64	0.01				3.23			
	Corrected total	95	1.59				238.47			
Clay Y	Water added (WA)	7	2.40	2038.29	***		310.26	1052.75	***	
	Aging	3	0.04	86.86	***		5.28	41.79	***	
	WA*Aging	21	0.01	3.63	**	0.011	1.63	1.84	*	0.14
	Error	64	0.01				2.69			
	Corrected total	95	2.47				319.86			
Clay E	Water added (WA)	7	2.45	2686.29	***		300.56	1583.23	***	
	Aging	3	0.04	99.56	***		4.17	51.31	***	
	WA*Aging	21	0.01	3.28	***	0.009	0.99	1.73	*	0.12
	Error	64	0.01				1.74			
	Corrected total	95	2.51				307.46			

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† SCI, single confidence interval.

Utomo and Dexter, 1981). Our runoff and soil loss data suggested that at AMC below the optimal range there was insufficient water in the soil to enable the formation of cohesive forces by both mechanisms. Conversely, AMC above the optimal range imposed an average distance between particles that was too big for the reoriented clay particles to cement adjacent particles into a stable structure (Gernuda et al., 1954; Shainberg et al., 1996).

The range of optimal AMC with respect to controlling runoff and soil loss (i.e., after addition of 2–4 mm of water to air dry soils) corresponded to pF values (4.1–2.4) that generally fall between wilting point and field capacity. The sizes of the pores that hold water at these matric potentials range from 5 nm to 10 μm. Pores in this size range belong to interdomain porosity (Moutier et al., 1998). Domains are considered as structural units of the clay fabric and comprise of overlapping and interspersing quasi-crystals, with the latter consisting of 5 to 10 clay platelets arranged mostly in a parallel alignment (Moutier et al., 1998). The calculated size range of the water-filled pores that was proposed to be active in the aging process in our study supported the hypothesis of Shainberg et al. (1996) that clay movement and reorientation or better arrangement (Blake and Gilman, 1970) is a key factor in the development of cohesive forces during aging.

With the exception of a few cases, the pF values for 2- to 4-mm water–added treatments (i.e., the optimal AMC levels) did not exceed those for 0- to 1-mm treatments in all the aging treatments (Fig. 2). Thus, it can be generalized that although the matric potential in the soil increased with the increase in aging duration, the matric potential for AMC of 2 to 4 mm stayed within the pF range (4.1–2.4) where it was effective in enhancing cohesive forces between particles. Consequently, the observed decrease in runoff and soil loss with the increase in aging duration can be ascribed to the favorable impact of longer aging on the development and strengthening of the cohesion forces within and between soil particles that improved the soil's resistance to seal formation and led to smaller loads of runoff and soil loss.

Effects of Clay Content

In general, runoff levels in the loam, sandy clay, and Clay (Y) were comparable; however, runoff from the Clay (E) soil was lower than that obtained in the other three soils at all of the aging durations studied (Fig. 3). A similar observation was made by Mamedov and Levy (2001). Evidently, the high clay content in the Clay (E) (Table 1) helped stabilizing the aggregates in this soil (Kemper and Koch, 1966) to a level where seal formation and runoff production were less severe compared with the other three soils tested.

Effects of AMC (expressed as pF) on runoff and soil loss in 3- to 7-d aging duration are presented in Fig. 5. For each soil, a general linear model and a mixed linear test model for ANOVA and mean separation tests were used. There were no differences between the results of the two models. Therefore, to easily compare treatment means of each treatment (for each soil), the least significant differences test was used (Tukey's HSD; SAS Institute, 1999).

Soil losses in the two clay soils were lower than those for the loam and sandy clay soils for any given aging duration and AMC (Fig. 4 and 5). Furthermore, with the exception of the 0.01-d aging duration, a comparison of the lowest amount of soil loss obtained in each soil among the four soils, for any given aging duration, reveled that soil loss was inversely related to clay content. The decrease in soil loss with the increase in clay content was linear for 3 and 7 d of aging (Fig. 6). For instance, at 3- to 7-d aging, soil loss in Clay (E) soil (<500 g m^{-2}) was 1.5 to 2 times less than in loam (>750 g m^{-2}). At these AMC (2–4 mm) levels (pF 4.1–2.4), the effects of aging were more pronounced for clay soils.

Reproduced from Soil Science Society of America Journal. Published by Soil Science Society of America. All copyrights reserved.

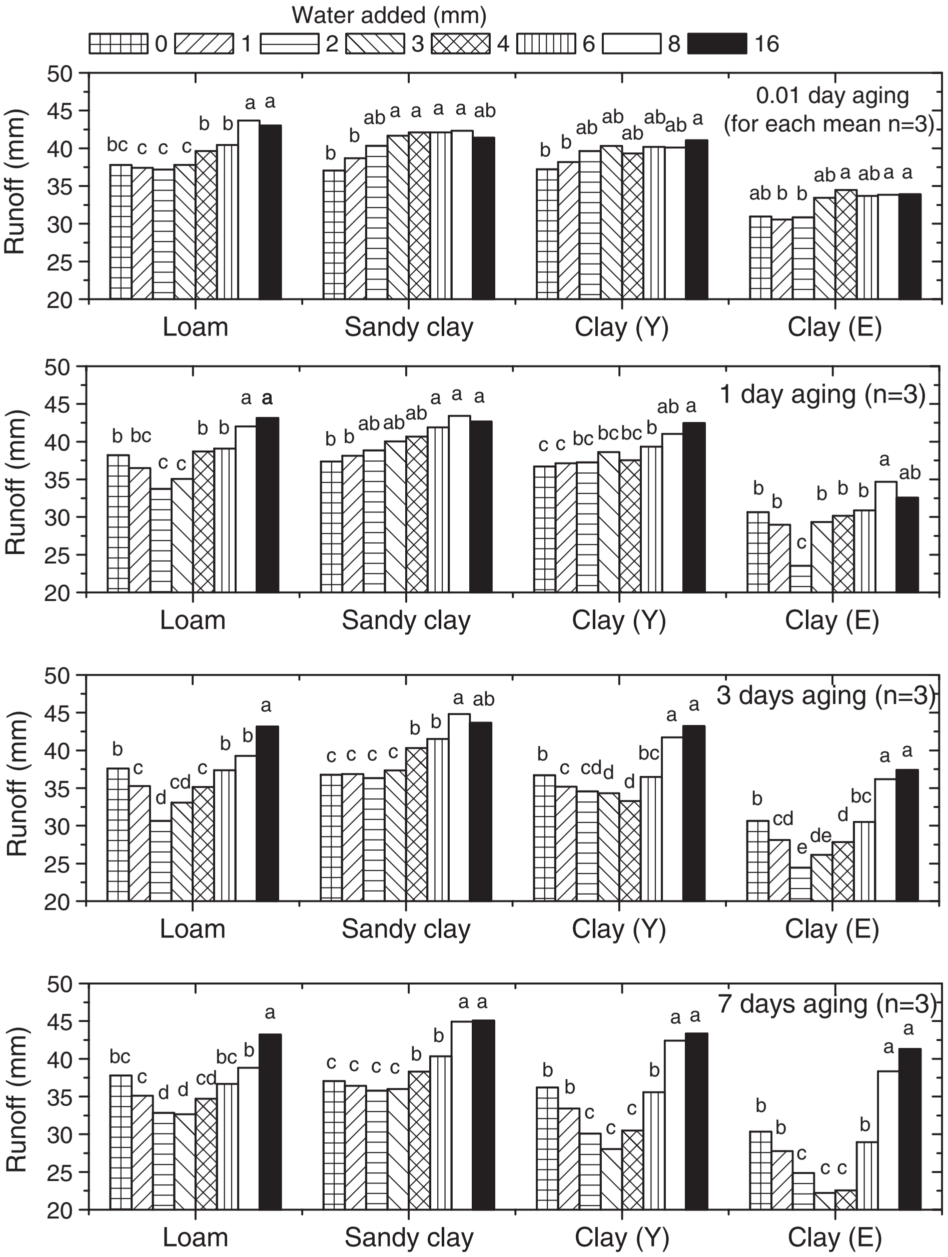

Fig. 3. Calculated runoff volumes from the 60-mm rain storms for the different aging periods as a function of soil type and amount of water added. For a giving aging period and within a soil type, columns labeled with same letter are not significantly different at $P < 0.05$. Within a soil, columns from left to right represent AMC derived from 0, 1, 2, 3, 4, 6, 8, and 16 mm of water added.

Generally, our results were in agreement with those of some former studies (e.g., Wischmeier et al., 1971; Meyer and Harmon, 1984; Ben-Hur et al., 1985) that concluded that medium textured soils were more susceptible to erosion than fine-textured soils. Meyer and Harmon (1984) suggested that clay soils were characterized by a cohesive structure and were, thus, difficult to detach. However, more recent studies (e.g., Truman and Bradford, 1990; Le Bissonnais et al., 1995) did not observe a distinct link between soil loss and clay content for air-dry or moist samples. Le Bissonnais et al. (1995) pointed out that complex interactions exist between soil properties and physical parameters in the erosion process. It is therefore possible that under certain experimental conditions the favorable impact of clay on soil structural stability, and thus on reducing its susceptibility to detachment, may be obscured in some soil types. Hence, different relationships between soil loss and clay content may exist.

We observed greater soil loss in the loam and sandy clay than in the clay soils, especially under extreme AMC levels (Fig. 4 and 6), which is characteristic of cultivated fields in semiarid and arid zone. Thus, management practices should be directed at maintaining moderate soil moisture levels particularly in soils with low clay content. Because antecedent soil moisture content and

Reproduced from Soil Science Society of America Journal. Published by Soil Science Society of America. All copyrights reserved.

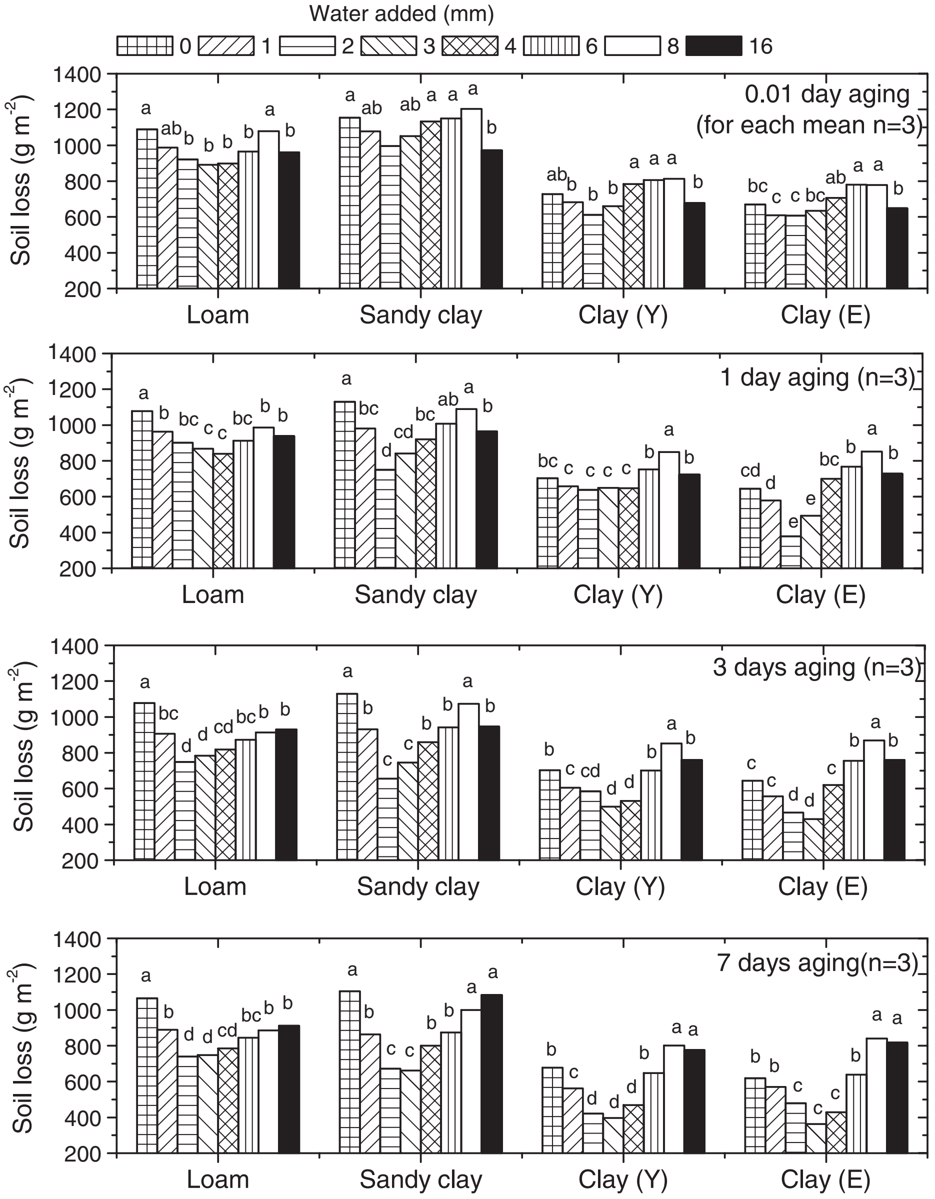

Fig. 4. Measured total soil loss from the 60-mm rain storms for the different aging periods, as a function of soil type and amount of water added. For a giving aging period and within a soil type, columns labeled with same letter are not significantly different at $P < 0.05$. Within a soil, columns from left to right represent AMC derived from 0, 1, 2, 3, 4, 6, 8, and 16 mm of water added.

aging greatly affect runoff and sediment transport potential, the management should be aimed at minimizing the potential of soil moisture variations using practices such as conservation tillage (minimum till or no-till known by residue level) and cover crops, predominantly on areas containing soils with high potential for erosion and also nutrient loss (McDowell and Sharpley, 2002).

Relationship Between Runoff and Soil Loss

Averaging the runoff values at the aforementioned optimal AMC levels (2–4 mm of water added to air-dry soil, pF ~4.1–2.4), for each soil and expressing it as the ratio of runoff at a given aging duration to the runoff at no aging (i.e., 0.01 d) indicated that runoff decreased with the increase in aging duration (Fig. 7). A similar trend was observed for the relative soil loss (Fig. 7). The decrease in the relative soil loss with the increase in aging duration was similar to the decrease in relative runoff, with the exception of sandy clay soil. This similarity in the behavior of soil loss and runoff in the optimal AMC treatments should not be considered as trivial. The coefficient of determination (r^2) values of linear regression analysis between the runoff and soil loss for these optimal AMC treatments in each of the four soils were very high (>0.91). Conversely, r^2 of a linear regression analysis between the entire runoff and soil loss data (for all AMC studied) in each soil were significantly lower, particularly for soils with lower clay content (0.35, 0.21, 0.77, and 0.75 for the loam, sandy

Reproduced from Soil Science Society of America Journal. Published by Soil Science Society of America. All copyrights reserved.

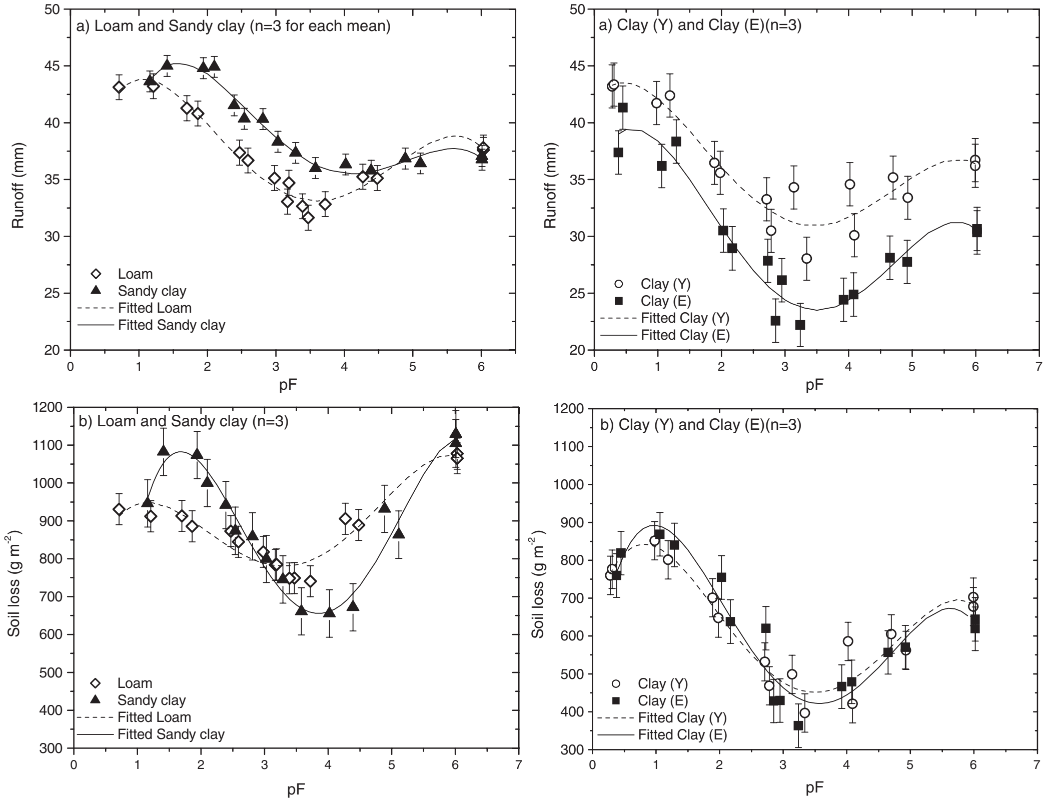

Fig. 5. Effect of AMC (expressed as pF) on (a) runoff and (b) soil loss in 3- to 7-day aging duration. Runoff and soil loss data were fitted to the pF data by a polynom of the fourth order ($r^2 > 0.90$, $P < 0.01$ in all cases). Bars indicate the least significant differences at $P < 0.05$. Means are significantly different where bars do not overlap.

clay, Clay Y, and Clay E, respectively), than that for the optimal AMC treatments. Seal formation may affect soil erosion in opposite ways: (i) Seal development increases the shear strength of the soil surface (Bradford et al., 1987) and thus reduces soil detachment (Moore and Singer, 1990); and (ii) seal formation increases runoff, which in turn increases the removal of detached sediments. By contrast, runoff is considered to be a direct result of seal formation. It has been suggested by Young and Wiersma (1973) that in small plots (as was the case in our study) the amount of the detached material that is removed is dictated by the volume of runoff flow. In

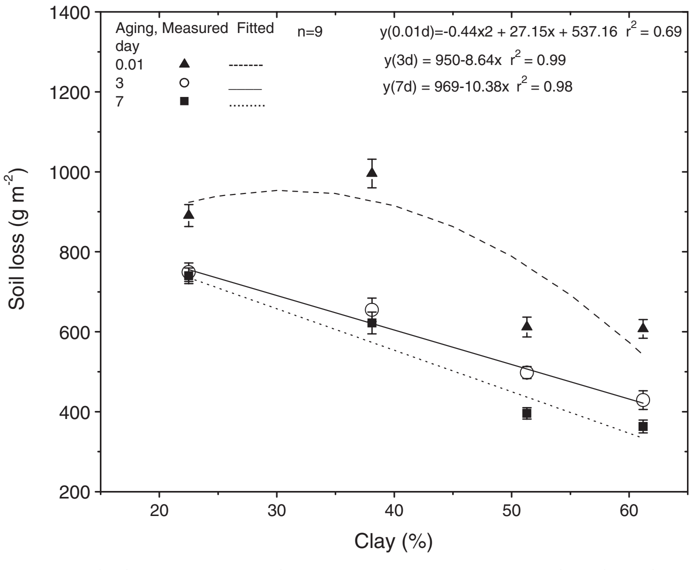

Fig. 6. Lowest measured soil loss from each soil (for the 2–4 mm of water added treatments) as a function of clay content for a given aging duration. Bars indicate two standard errors.

Reproduced from Soil Science Society of America Journal. Published by Soil Science Society of America. All copyrights reserved.

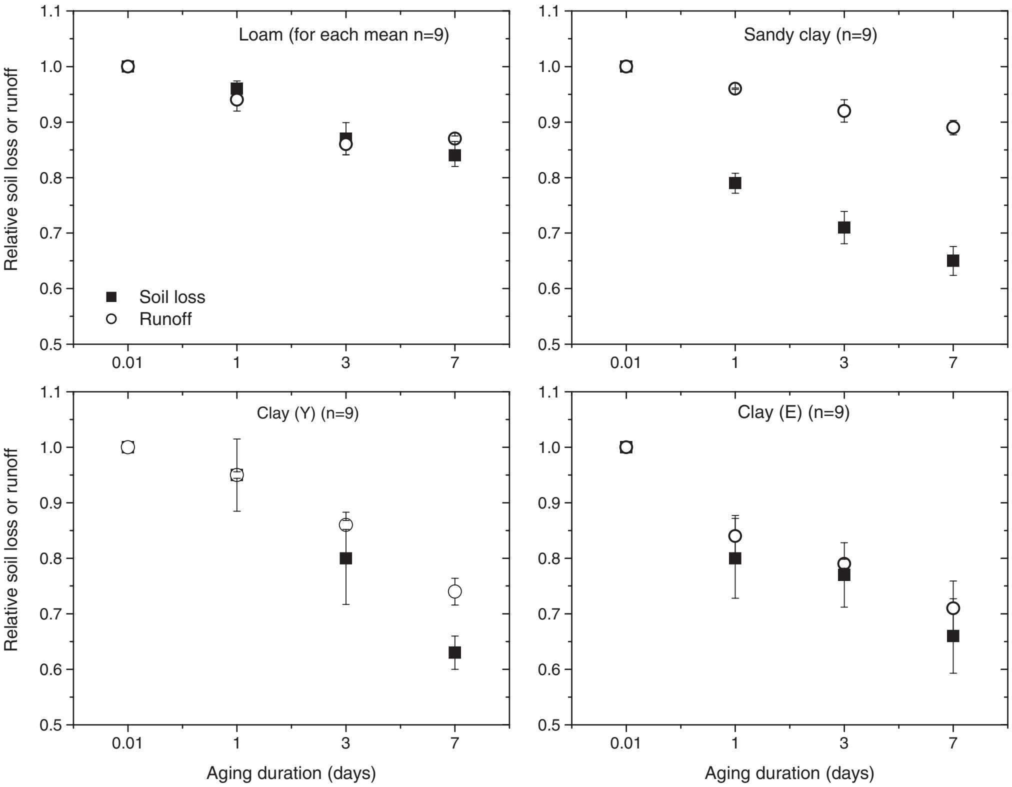

Fig. 7. Relative runoff or soil loss, expressed as the ratio of runoff or soil loss at a given aging duration to the runoff or soil loss at no aging (0.01 d). The ratios were calculated for the average runoff or soil loss data obtained from the 2, 3, and 4 mm of water added treatments. Bars indicate two standard errors.

our study, the predominant direct impact of runoff on soil loss was restricted to the optimal AMC treatments only. Our data suggested, therefore, that the sole dependence of soil loss on runoff was limited to conditions under which soil resistance to seal formation was enhanced (i.e., optimal AMC that varied between wilting point and field capacity). Under conditions where the soil was more susceptible to seal formation, runoff, and soil loss (i.e., AMC values lower or higher than the optimal range), other factors (e.g., initial aggregate slaking by fast wetting, detachment of particles by the impact of raindrop, etc.) in addition to runoff, may control soil loss.

CONCLUSIONS

We studied the effects of AMC and aging on seal development (expressed in terms of runoff volume) and soil erosion on four smectitic soils. Our results revealed the existence of an optimal range of AMC (2–4 mm of water added, corresponding to pF values in the range of 4.1–2.4) at which the runoff and erosion levels were lower, at times even by 30%, than those obtained at AMC levels above or below the optimal range. Furthermore, increasing aging duration resulted in a 15 to 40% decrease in runoff and soil loss at this optimal AMC range in comparison to no aging; effects of aging at optimal AMC were of greater magnitude in clay soils. The similar manner at which runoff and soil loss decreased with the increase in aging duration at the optimal AMC range indicated that, under our experimental conditions, runoff was the main precursor for soil loss.

The combined favorable impact of AMC and aging on improving soil stability was associated with water-filled pores that were of the size belonging to the clay fabric (pF 2.4–4.2). 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.

Our results emphasize that the role of surface conditions, and particularly that of AMC and aging, in determining soil surface structural stability and its resistance to seal development and soil loss production is not of negligible importance. Most erosion models consider only soil inherent properties (mainly texture) in the computation process of soil erosion. The results of this study are important for soil erosion modeling (i.e., to improve the prediction capabilities of models such us WEPP, soil conditions before erosive rainstorms such as AMC, wetting, and aging should be considered). In fact, many well established relationships in soil moisture and wetting rate effects on sealing, crusting, and runoff have yet to be incorporated in process-based erosion models. Management practices could be adapted to diminish the severe soil moisture variation, where ever possible, besides conservation tillage (minimum till or no-till) to introduce short spans of irrigation to maintain the soil surface at a desired AMC level before expected rainstorms to decrease soil susceptibility to seal formation, runoff, and soil loss.

Reproduced from Soil Science Society of America Journal. Published by Soil Science Society of America. All copyrights reserved.

REFERENCES

Agassi, M., and G.J. Levy. 1991. Stone-cover and rain intensity: Effects on infiltration, erosion and water splash. Aust. J. Soil Res. 29: 565–575.

Agassi, M., I. Shainberg, and J. Morin. 1981. Effect of electrolyte concentration and soil sodicity on infiltration rate and crust formation. Soil Sci. Soc. Am. J. 48:848–851.

Al-Durrah, M.M., and J.M. Bradford. 1981. New methods of studying soil detachment due to water drop impact. Soil Sci. Soc. Am. J. 45: 949–953.

Attou, F., A. Bruand, and Y. Le Bissonnais. 1998. Effect of clay content and silt-clay fabric on stability of artificial aggregates. Eur. J. Soil Sci. 49:569–577.

Banin, A., and A. Amiel. 1970. A correlative study of the chemical and physical properties of a group of natural soils of Israel. Geoderma 3:185–198.

Ben-Hur, M., I. Shainberg, D. Bakker, and R. Keren. 1985. Effect of soil texture and $CaCO_3$ content on water infiltration in crusted soil as related to water salinity. Irrig. Sci. 6:281–294.

Betzalel, I., J. Morin, Y. Benyamini, M. Agassi, and I. Shainberg. 1995. The effect of water drop energy on seal formation. Soil Sci. 159: 13–22.

Blake, G.R., and R.D. Gilman. 1970. Thixotropic changes with aging of synthetic soil aggregates. Soil Sci. Soc. Am. Proc. 34:561–564.

Bradford, J.M., J.E. Ferris, and P.A. Remley. 1987. Interrill soil erosion processes: I. Effect of surface sealing on infiltration, runoff and soil splash detachment. Soil Sci. Soc. Am. J. 51:1566–1577.

Bradford, J.M., and C. Huang. 1990. Mechanism of crust formation: Physical components. p. 55–72. *In* M.E. Sumner and B.T. Stewart (ed.) Soil crusting: physical and chemical processes. Advances in soil science. Lewis Publishers, Boca Raton, FL.

Bradford, J.M., C.C. Truman, and C. Huang. 1992. Comparison of three measures of resistance of soil surface seals to raindrop splash. Soil Tech. 5:47–56.

Cruse, R.M., and W.E. Larson. 1977. Effect of soil shear strength on soil detachment due to raindrop impact. Soil Sci. Soc. Am. J. 41: 777–781.

Epema, G.F., and H.Th. Riezebos. 1983. Fall velocity of water drops at different heights as a factor influencing erosivity of simulated rain. Catena Supplement 4:1–17.

Farres, P.J. 1987. The dynamics of rain splash erosion and the role of soil aggregate stability. Soil Sci. Soc. Am. J. 14:119–130.

Francis, P.B., and R.M. Cruse. 1983. Soil water matrix potential effects on aggregate stability. Soil Sci. Soc. Am. J. 47:578–581.

Froese, J.C., R.M. Cruse, and M. Ghaffarzadeh. 1999. Erosion mechanics of soils with an impermeable subsurface layer. Soil Sci. Soc. Am. J. 63:1836–1841.

Gerard, C.J. 1965. The influence of soil moisture, soil texture, drying conditions and exchangeable cations on soil strength. Soil Sci. Soc. Am. Proc. 29:641–645.

Gernuda, C.F., R.M. Smith, and J. Vicente-Chandler. 1954. Influence of initial soil moisture condition on resistance of macroaggregates to slaking and water-drop impact. Soil Sci. 77:19–27.

Goldberg, S., D.L. Suarez, and R.A. Glaubig. 1988. Factors affecting clay dispersion and aggregate stability of arid-zone soils. Soil Sci. 146:317–325.

Gupta, S.C., A. Hadas, B. Voorhess, D. Wolf, W.E. Larson, and P.P. Sharma. 1990. Development of guides on the susceptibility of soils to excessive compaction. Final report to the Binational Agricultural Research & Development (BARD) Fund. Proj. no. US-973–85. BARD, Bet Dagan, Israel.

Kazman, Z., I. Shainberg, and M. Gal. 1983. Effects of low levels of exchangeable Na and applied phosphogypsum on the infiltration rate of various soils. Soil Sci. 35:184–192.

Kemper, W.D., and E.J. Koch. 1966. Aggregate stability of soils from western U.S. and Canada. Technical Bulletin No. 1355, USDA.

Kemper, W.D., and R.C. Rosenau. 1984. Soil cohesion as affected by time and water content. Soil Sci. Soc. Am. J. 48:1001–1006.

Kemper, W.D., R.C. Rosenau, and A.R. Dexter. 1987. Cohesion development in disrupted soils as affected by clay and organic matter content and temperatures. Soil Sci. Soc. Am. J. 51:860–867.

Kjaergaard, C., L.W. de Jonge, P. Moldrup, and P. Schjonning. 2004. Water dispersible colloids: Effects of measurement method, clay content, initial soil matric potential and wetting rate. Vadoze Zone J. 3:403–412.

Klute, A. (ed.) 1986. Methods of soil analysis. Part 1. 2nd ed. Agron. Monogr. 9. ASA and SSSA. Madison, WI.

Lado, M., M. Ben-Hur, and I. Shainberg. 2004. Soil wetting and texture effects on aggregate stability, seal formation and erosion. Soil Sci. Soc. Am. J. 68:1992–1999.

Le Bissonnais, Y. 1990. Experimental study and modeling of soil surface crusting processes. Catena Supplement 17:13–28.

Le Bissonnais, Y. 1996. Aggregate stability and assessment of soil crustability and erodibility. I. Theory and methodology. European J. Soil Sci. 47:425–437.

Le Bissonnais, Y., and M.J. Singer. 1992. Crusting, runoff and erosion response to soil water content and successive rainfalls. Soil Sci. Soc. Am. J. 56:1898–1903.

Le Bissonnais, Y., B. Renaux, and H. Delouche. 1995. Interactions between soil properties and moisture content in crust formation, runoff and interrill erosion from tilled loess soils. Catena 25: 33–46.

Levy, G.J., and A.I. Mamedov. 2002. High energy moisture characteristics aggregate stability as a predictor for seal formation. Soil Sci. Soc. Am. J. 66:1603–1609.

Levy, G.J., J. Levin, and I. Shainberg. 1997. Prewetting rate and aging effects on seal formation and interrill soil erosion. Soil Sci. 162: 131–139.

Loch, R.J. 1994. Structure breakdown on wetting. p. 113–132. *In* H.B. So, G.D. Smith, S.R. Reine, B.M. Schafer, and R.J. Loch (ed.) Sealing, crusting and hardsetting soils. Australian Soil Sci. Soc., Queensland Branch, Brisbane, Australia.

Luk, S.H. 1985. Effect of antecedent soil moisture content on rainwash erosion. Catena 12:129–139.

Mamedov, A.I., and G.J. Levy. 2001. Clay dispersivity and aggregate stability effects on seal formation and erosion in effluent irrigated soils. Soil Sci. 66:631–639.

Mamedov, A.I., G.J. Levy, I. Shainberg, and J. Letey. 2001. Wetting rate and soil texture effect on infiltration rate and runoff. Aust. J. Soil Res. 30:1293–1305.

McDowell, R.W., and A.N. Sharpley. 2002. The effect of antecedent moisture conditions on sediment and phosphorus loss during overland flow: Mahantango Creek catchment, Pennsylvania, USA. J. Hydrol. Processes 16:3037–3050.

McIntyre, D.S. 1958. Permeability measurements of soil crusts formed by raindrop impact. Soil Sci. 85:185–189.

Meyer, L.D., and W.C. Harmon. 1984. Susceptibility of agricultural soils to interrill erosion. Soil Sci. Soc. Am. J. 48:1152–1157.

Moore, D.C., and M.J. Singer. 1990. Crust formation effects on soil erosion processes. Soil Sci. Soc. Am. J. 54:1117–1123.

Morin, J., and Y. Benyamini. 1977. Rainfall infiltration into bare soils. Water Res. Res. 13:813–817.

Moutier, M., I. Shainberg, and G.J. Levy. 1998. Hydraulic gradient, aging and water quality effects on the hydraulic conductivity of a vertisol. Soil Sci. Soc. Am. J. 62:1488–1496.

Page, A.L., R.H. Miller, and D.R. Keeney (ed.). 1986. Methods of soil analysis. Part 2. 2nd ed. Agron. Monogr. No. 9. ASA and SSSA, Madison, WI.

Panabokke, C.R., and J.P. Quirk. 1957. Effect of initial water content on stability of soil aggregates in water. Soil Sci. 83:185–195.

Reichert, J.M., and L.D. Norton. 1994. Aggregate stability and rain-impacted sheet erosion of air-dried and prewetted clayey surface soils under intense rain. Soil Sci. 158:159–169.

SAS Institute. 1999. SAS guide for personal computers—Version 6.07. SAS Institute, Cary, NC.

Schofield, R.K. 1935. The pF of the water in soil. p. 37–48. Transactions of 3rd International Congress of Soil Science, Volume 2. Plenary Session Papers. Oxford.

Shainberg, I., and G.J. Levy. 1992. Physiochemical effects of salts upon infiltration and water movement in soils. p. 37–94. *In* R.J. Wagenet, P. Baveye, and B.A. Stewart (ed.) Interacting processes in soil science. Advances in Soil Science. Lewis Publishers, Boca Raton, FL.

Shainberg, I., D. Goldstein, and G.J. Levy. 1996. Rill erosion dependence on soil water content, aging and temperature. Soil Sci. Soc. Am. J. 60:916–922.

Shainberg, I., A.I. Mamedov, and G.J. Levy. 2003. Role of wetting rate and rain energy in seal formation and erosion. Soil Sci. 168:54–62.

Truman, C.C., and J.M. Bradford. 1990. Effect of antecedent soil moisture on splash detachment under simulated rainfall. Soil Sci. 150:787–798.

Truman, C.C., J.M. Bradford, and J.E. Ferris. 1990. Antecedent water content and rainfall energy influence on soil aggregates breakdown. Soil Sci. Soc. Am. J. 54:1385–1392.

Utomo, W.H., and A.R. Dexter. 1981. Age hardening of agricultural top soils. J. Soil Sci. 32:335–350.

Wangemann, S.G., R.A. Kohl, and P.A. Molumeli. 2000. Infiltration and percolation influenced by antecedent soil water content and air entrapment. Trans. ASAE 43:1517–1523.

Wischmeier, W.H., C.B. Johnson, and B.V. Cross. 1971. A soil erodibility monograph for farmland and construction sites. J. Soil Water Cons. 20:150–152.

Young, R.A., and J.L. Wiersma. 1973. The role of rainfall impact in soil detachment and transport. Water Resour. Res. 9:1629–1636.

Reproduced from Soil Science Society of America Journal. Published by Soil Science Society of America. All copyrights reserved.