EFFECTS OF SURFACE TREATMENT ON SURFACE SEALING, RUNOFF, AND INTERRILL EROSION

X. C. Zhang, W. P. Miller, M. A. Nearing, L. D. Norton

ABSTRACT. *Surface treatment influences the nature and extent of seal/crust formation, which affects runoff and erosion. This study evaluated the effects and longevity of soil amendments, tillage, and screen cover on runoff and interrill erosion on a Cecil sandy loam (clayey, kaolinitic, thermic* Typic Kanhapludult*) under natural rainfall conditions. Six field plots (3.5 × 0.9 m) with a slope of 0.06-m m*$^{-1}$ *were used in the study. Three treatments (control, screen cover, crust-breaking shallow tillage) were studied in duplicate in the first two-month period, and another three (control, anionic polyacrylamide (PAM), and phosphogypsum) in a subsequent five-month period. Total runoff and soil loss were 69, 61, and 47 mm and 5.3, 1.6, and 4.3 Mg ha*$^{-1}$ *for the control, screen cover, and tillage treatments, respectively. Compared with control, screen cover reduced soil loss significantly but not runoff, while tillage reduced runoff more than soil loss. Total runoff and soil loss for the control, gypsum, and PAM treatments were 146, 48, and 81 mm and 3.1, 2.6, and 2.5 Mg ha*$^{-1}$*, respectively. Runoff was reduced by 67% and 44% for the gypsum and PAM relative to control and soil loss by 16% and 19%, showing gypsum and PAM were more effective in reducing runoff than soil loss. Runoff was significantly reduced in the gypsum and PAM treatments in the five months following surface application. Results showed screen cover and tillage temporally reduced or delayed seal/crust formation, while the effects of gypsum and PAM were more persistent. Combined with earlier findings, it appears that a combination of physical and chemical treatments is the best practice for controlling surface sealing and reducing runoff and erosion on this soil.*

Keywords. *Soil amendment, Surface sealing, Water infiltration, Interrill erosion.*

Surface sealing and soil crusting are common to many agricultural soils, which often increase surface runoff and erosion. Surface seals substantially reduce water infiltration because of their low hydraulic conductivity. For example, the hydraulic conductivity of surface seals for the Cecil soil used in this study was one to two orders less than that of the underlying unsealed soil (Chiang et al., 1993). Typically steady-state infiltration rate on this sealed soil approached 2 mm h^{-1} or less. It has been reported that cover and chemical amendments such as gypsum and organic polymer are effective in reducing seal-crust formation and increasing final infiltration rate (Mannering and Meyer, 1963; Miller, 1987; Shainberg, 1992; Norton et al., 1993; Zhang and Miller, 1996b).

During seal formation, soil bulk density and shear strength in the vicinity of the soil surface increase, and consequently soil splash or splash detachment decreases (Bradford et al., 1986; Slatter and Bryan, 1992). The effects of surface sealing on interrill erosion can be either positive or negative, depending on soil and topographic conditions. Interrill erosion is composed of two major processes: (1) detachment by raindrop impact, and (2) transport by thin overland flow. In general, sealing tends to increase interrill soil loss by increasing runoff (Miller, 1987; Miller and Scifres, 1988) because interrill erosion is often limited by the transport capacity of shallow overland flow. However, decreases of interrill soil loss with seal formation have also been reported (Poesen and Govers, 1985; Norton, 1987). This discrepancy is because seal formation affects both processes. Because detachment rate decreases as a seal forms, seal formation may reduce the total soil loss if detachment is limiting. Conversely, larger runoff volumes produced under sealed conditions, coupled with enhanced transport capacity by raindrop impact (Kinnell, 1991), may increase interrill soil loss rate if shallow overland transport is limiting.

Seal formation involves two major complementary mechanisms: (1) physical disintegration of soil aggregates by raindrop impact and slaking upon wetting followed by consolidation at the soil surface; and (2) chemical dispersion of surface clay particles and subsequent illuviation of these particles into the region immediately beneath the surface, where dispersed clay particles clog pores and form an illuviated zone (Chen et al., 1980; Agassi et al., 1981). Physical processes predominate when soils with high electrical conductivity (EC) or low exchangeable sodium percentage (ESP) are exposed to high intensity rains. Otherwise, chemical processes supplement or enhance the physical processes (Miller and Scifres, 1988; Shainberg et al., 1989). The interaction between the two mechanisms becomes significant when soils with low ESP, low EC, and a dominant 1:1 clay mineralogy are exposed to rain with low EC (Zhang and

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Miller, 1996b). Physical processes can be reduced by surface mulch and canopy cover that protect soil aggregates from raindrop impact (Mannering and Meyer, 1963; Lattanzi et al., 1974). Chemical processes (clay dispersion) can be prevented by gypsum addition that increases soil solution electrolyte concentration (Miller, 1987; Shainberg et al., 1989; Norton et al., 1993) and exchangeable calcium fraction on the exchange sites. Organic polymers stabilize soil aggregates and flocculate clay particles, and therefore tend to suppress both mechanisms (Shainberg et al., 1990; Levy et al., 1992; Agassi and Ben-Hur, 1992).

We hypothesize that the effects of surface sealing and soil crusting on runoff and interrill erosion depend largely on the extent and nature of the mechanisms involved in seal formation and can be controlled by physical and chemical surface treatments. The objective of this study was to evaluate the effectiveness and persistence of different surface treatments on seal-crust formation, surface runoff, and interrill erosion for a Georgia Ultisol under natural rainfall conditions.

MATERIALS AND METHODS

This study was conducted in Georgia USA on a Cecil sandy loam soil (clayey, kaolinitic, thermic *Typic Kanhalpudult*). The soil texture of the Ap horizon was composed of 77% sand, 14% silt, and 9% clay. The organic matter content was 1.5%. The cation exchange capacity (CEC) calculated by summation of bases was 5.3 $\mathrm{cmol_c\ kg^{-1}}$, and the exchangeable sodium percentage (ESP) calculated by dividing exchangeable sodium by CEC was 1.9%. Water dispersable clay on a clay basis was 93% (24 h shaking in deionized water). Soil pH measured in deionized water (1:2 by weight) was 5.9. Soil aggregates were easily disrupted by raindrop impact, and the soil was susceptible to seal formation (Miller, 1987; Miller and Scifres, 1988).

Soybeans were grown on the site under conventional tillage before this experiment. Whole plants were removed from the site during site preparation. The site was disked three times and the soil was well mixed to a 15-cm depth. Six plots, 3.5 m long × 0.92 m wide, were bounded with metal borders. Runoff drained into a covered barrel at the lower end of each plot. Slope gradient was approximately 0.06 $\mathrm{m\ m^{-1}}$. The soil surface was smoothed by raking and was kept free of weeds by periodically spraying with a herbicide. Runoff and soil loss from 10 storms were collected prior to treatment to determine plot variability. Averaged CVs over the 10 storms were 16% for soil loss and 10% for runoff. After the initial assessment, all plots were hand-hoed and then smoothed by raking before initiation of surface treatments.

Five treatments were used to influence seal-crust formation: (1) control, bare soil exposed to rainfall with no physical treatment or chemical addition (other than the herbicide); (2) screen cover (physical), one layer of window screen was suspended 0.15 m above the soil surface to dissipate raindrop impact energy; (3) tillage (physical), soil surfaces were raked manually to a depth of about 25 mm to break crusts and then were smoothed by gently tapping and scraping with a wood block to remove micro relief after each rain; (4) gypsum (chemical treatment, phosphogypsum from Bartow, Florida; 95% $CaSO_4{\cdot}2H_2O$), gypsum powder was surface applied at 5 $\mathrm{Mg\ ha^{-1}}$ before the test to prevent clay dispersion; (5) PAM, 1-kg $\mathrm{m^{-3}}$ PAM solutions (prepared in 2.5 mol $\mathrm{m^{-3}}$ gypsum solution) were uniformly sprayed on dried soil surfaces at the 20 kg PAM $\mathrm{ha^{-1}}$ rate, and the soil surfaces were allowed to dry after the spraying.

Screen cover that does not affect runoff characteristics and surface storage was used to isolate the effects of surface sealing and crusting by raindrop impact on runoff and erosion. For the gypsum treatment, 5 $\mathrm{Mg\ ha^{-1}}$ rate was based on a previous study conducted on a similar Cecil soil (Miller, 1987). PAM polymer used was Magnifloc 836A (American Cyanamide Corp., Stamford, Conn.). It is a medium-charge anionic polymer (20% hydrolysis) and has a high molecular weight of 15 million g $\mathrm{mol^{-1}}$. PAM was slowly dissolved in 2.5 mol $\mathrm{m^{-3}}$ gypsum solution to obtain 1 kg $\mathrm{m^{-3}}$ PAM concentration. For the 20 kg $\mathrm{ha^{-1}}$ application rate, 2 L $\mathrm{m^{-2}}$ was needed and the wetting zone depth was < 5 mm for the dry and smooth surfaces. Gypsum addition to the PAM solutions was to reduce the viscosity of the PAM solution and to establish cation bridges between negatively charged clay particles and PAM molecules. The 20 kg $\mathrm{ha^{-1}}$ application rate was based on the results from a simulated rainfall study on the same soil (Zhang and Miller, 1996a) and on other soils for surface application (Levy et al., 1991; Shainberg and Levy, 1994).

Treatments were randomly assigned to plots with two replicates each. Control and physical (cover and tillage) treatments were studied during the first period from 10 July to 26 August 1991. Then all plots were hand-hoed and prepared anew for chemical treatments for the second period of study, assuming cover and tillage treatments did not have residual effects on subsequent treatments. Control, gypsum and PAM treatments were tested from 11 November 1991 to 9 March 1992, which were followed by a two-month extended observation during which only runoff was measured.

Plots were visited periodically as well as after large storms. Amounts of rainfall, runoff, and soil loss were measured. Runoff was passed through a 53-μm sieve for sand-sized fraction of sediment. Clay plus silt fraction was determined by drying an aliquot of well mixed solution after passing through the sieve. Runoff and soil loss from each individual storm were analyzed using the Duncan's Multiple Range Test to test for the significant difference between the control and each treatment. In addition, a paired-comparison t-test was used to test for significance between each treatment and control using all individual observations during each period of study. This type of test examines whether the mean difference from each paired observations differs from zero. Thus it evaluates the effectiveness and consistency of each treatment as compared to the control treatment. Lack of a significance test for each individual storm with the Duncan's test due to insufficient replications can be remedied by using the paired t-test in which each storm is treated as an independent observation. This test reveals the significance of each treatment during the period of study rather than for a single event, and can be used as a supplement to the Duncan's test.

RESULTS AND DISCUSSION

EFFECTS OF SCREEN COVER AND TILLAGE ON RUNOFF AND INTERRILL EROSION

Runoff from the tillage treatment was significantly less than from the control treatment in six of eight storms (table 1) except for the first rain when both treatments were newly prepared and not differentiated. In general, the degree of seal formation during a rain increases with the increase in cumulative raindrop impact energy (Agassi et al., 1985; Bradford and Huang, 1992), and rainfall energy is related to rainfall amount and intensity. In this study, the effectiveness of the tillage treatment in reducing seal formation tended to decrease as total rainfall amount increased. The runoff ratios (the ratio of runoff from the tillage treatment to that from the control) were correlated to rainfall amounts when excluding the first two storms in the analysis ($r = 0.76$, $P = 0.05$). The second storm was excluded because the soil surfaces were only raked but not smoothed by tapping and scraping with a wood block to remove micro relief. The correlation can be explained by the degree of seal formation combined with soil compaction or consolidation. Zhang and Miller (1996b) reported that raindrop impact, clay dispersion, and their interactions were responsible for seal formation on this soil under simulated rainfall conditions. If rainfall amount or energy was not high enough to cause seal formation such as in storms 3 and 4, little runoff was produced by the tillage treatment (table 1). For larger storms, which often occurred in high intensity during the summer season in the region, seals would form more rapidly, and greater runoff ratios would be expected. Using a similar Cecil soil, Chiang et al. (1993) studied seal development under a constant rainfall intensity of 50 mm h^{-1} and reported that complete sealing occurred within 20 min of rainfall. Thus, due to the formation of a new seal, total runoff from the tillage treatment tended to approach that of the control treatment for larger storms.

For the cover treatment, runoff from the first storm was reduced as compared to the control treatment (table 1, $P = 0.1$). This was because screen cover reduced raindrop impact energy, and minimized the physical processes of seal formation. However, runoff after the first three storms increased more rapidly (fig. 1a, table 1), indicating complete formation of a surface seal. A simulated rainfall study with a water EC of 0.2 dS m^{-1} showed surface seals were gradually developed even under two layers of screen cover during a 30-min rain (Zhang and Miller, 1996b). This suggested that this low EC and low ESP soil was susceptible to seal formation even under low energy of raindrop impact. As a result of seal formation, runoff from the cover treatment was not less than from the control treatment after the first storm (table 1). Besides, one layer of screen cover, suspended 0.15 m above the soil surface, might have reduced soil evaporation, but no apparent differences in the soil surface wetness were observed during most of our site visits.

Table 1. Storm runoff and soil loss from the control, cover, and tillage treatments during the first period of the study (from 10 July to 26 August 1991)

Storm Number	Storm Date	Rainfall (mm)	Runoff* (mm) Control	Runoff* (mm) Cover	Runoff* (mm) Tillage	Soil Loss* (kg ha^{-1}) Control	Soil Loss* (kg ha^{-1}) Cover	Soil Loss* (kg ha^{-1}) Tillage
1	16 July	23.3	8.7	2.4†	9.0	1140	120†	844
2	19 July	27.5	9.3	5.4	2.2†	443	144	216
3	24 July	5.3	0.5	0.6	0	24	16	0†
4	2 Aug	3.5	0.5	0.7†	0†	39	27	0
5	7 Aug	10.0	5.1	6.1	3.3†	476	144	383
6	10 Aug	13.0	5.4	6.5	4.8	769	264†	813
7	12 Aug	20.5	18.0	19.8	15.3†	1437	516†	1349
8	15 Aug	14.7	6.5	5.7	4.5†	145	45†	170
9	26 Aug	19.8	15.2	13.6	7.6†	796	305	563
Total		137.7	69.1	60.9	46.7	5268	1582	4337
Mean		15.3	7.7	6.8	5.2‡	585	176‡	482‡

* Numbers are means of two replicates.

† Different from the control treatment at P = 0.1 for the same storm.

‡ Different from the control treatment at P = 0.05 using paired-comparison t-test.

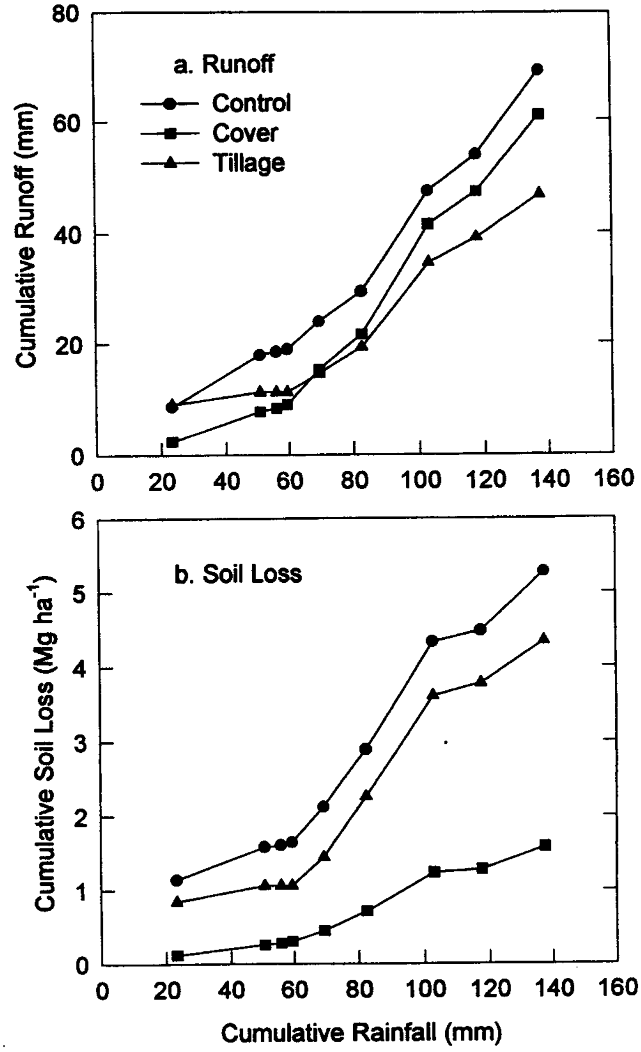

Figure 1–(a) Cumulative runoff, and (b) soil loss during the first period of the study (10 July to 26 Aug. 1991) as affected by the screen cover and shallow tillage treatments.

Interrill erosion was the dominant erosion process in this study because micro-rills and large scouring holes were not observed in any treatment. Cumulative soil losses from the cover and tillage treatments are plotted in figure 1b. Total soil loss from the cover treatment was reduced by approximately 70% compared with the control treatment. Four out of nine storms produced less soil loss in the cover treatment than in the control ($P = 0.1$, table 1). Dissipation of raindrop impact energy by a screen cover reduced raindrop detachment as well as the raindrop impact-induced enhancement of sediment transport of the thin sheet flow (Kinnell, 1991); resulting in a significant reduction in total soil loss compared with the control treatment even though the runoff volumes were similar.

For the tillage treatment, two offsetting mechanisms affected soil loss. Disturbance of preformed crusts increased loose erodible materials on the soil surface. On the other hand, disturbance of crusts reduced sediment transport capacity of runoff or shear strength of flowing water by reducing runoff. Together, tillage could have either increased or decreased interrill soil loss depending on the relative changes of surface soil strength and runoff shear. For smaller storms such as storms 3 and 4, most of rainfall infiltrated into the soil before the formation of a new seal, thus very little soil was lost. For the larger storms, soil losses did not differ from those of the control even though runoff volumes were significantly less in the tillage treatment (table 1). However, the paired-comparison t-test showed the tillage treatment overall reduced soil loss at the P = 0.05 level.

EFFECTS OF GYPSUM AND PAM ON RUNOFF AND INTERRILL SOIL LOSS

Gypsum and PAM prevented clay dispersion and reduced runoff for all the observations except for the third one in the gypsum treatment (table 2, P = 0.1), indicating a lesser degree of surface sealing in both treatments. Total runoff volumes during the study period for a total depth of 328 mm rainfall were reduced by 67% for gypsum and 44% for PAM (fig. 2a). This indicates that preventing clay dispersion and stabilizing soil aggregates reduced seal/crust formation on this soil. Runoff ratios during the study period were either remained relatively constant with time for the PAM treatment and decreased slightly for the gypsum treatment (table 2). These results were more profound than those from a related study on the same soil under simulated rainfall at a 90 mm h^{-1} intensity (Zhang and Miller, 1996b). Since rainfall intensity was normally low at the experimental site during the winter season when these data were collected, this discrepancy may indicate that gypsum was more effective in reducing runoff for lower intensity rains. For a given increase in steady state infiltration rate, percent reduction in runoff varies with rainfall intensity and duration after runoff generation. The greater the rainfall intensity and the shorter the duration, the lesser the reduction.

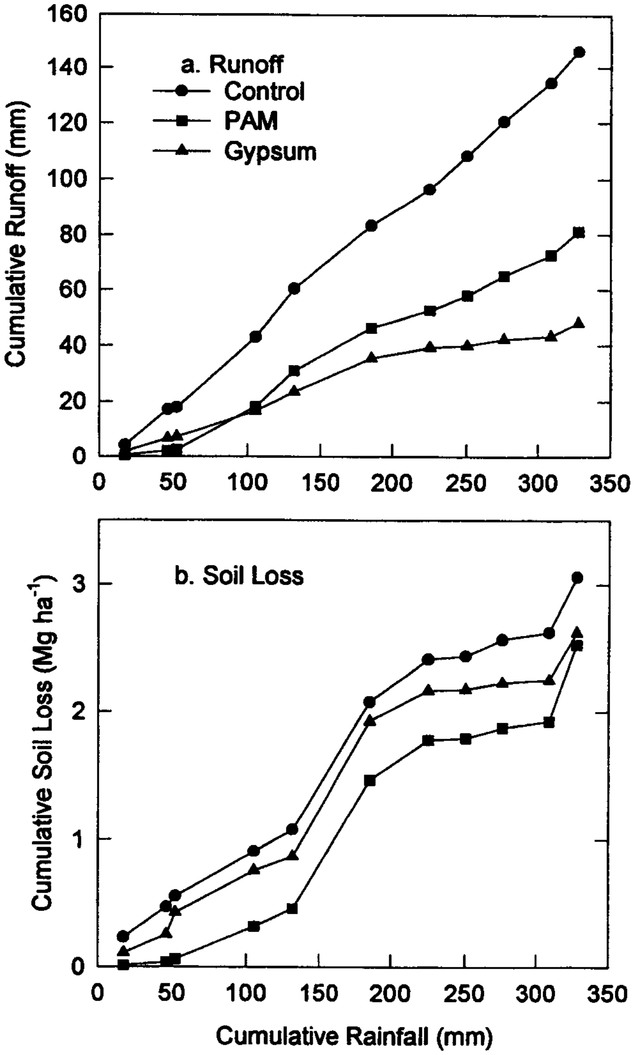

Figure 2–(a) Cumulative runoff, and (b) soil loss during the second period of the study (11 Nov. 1991 to 9 March 1992) as affected by the gypsum and PAM treatments.

Miller and Radcliffe (1992) reported similar results from a field study conducted on a closely related soil series (Appling sandy loam) at a nearby location under natural rainfall conditions. They found runoff from a 6 Mg ha^{-1} gypsum treatment was reduced by approximately 50% compared with control in the winter season, but no significant reduction was observed for the summer growing season. They attributed this discrepancy partially to the more erosive rains in the summer season and the washing-off of gypsum in the early season (in about one month after application). The effects of rainfall intensity can be an additional factor contributing to the discrepancy.

Table 2. Storm runoff and soil loss from the control, gypsum, and PAM treatments during the second period of the study (from 11 Nov 1991 to 9 March 1992)

Observation Number	Observation Date	Rainfall (mm)	Runoff* (mm)			Soil Loss* (kg ha^{-1})		
			Control	Gypsum	PAM	Control	Gypsum	PAM
1	22 Nov 91	17.5	4.1	1.9†	0.4†	233	110	13†
2	4 Dec 91	28.7	13.0	4.7†	1.8†	236	144	23†
3	14 Dec 91	5.9	0.8	0.5	0.2†	86	173	25
4	29 Dec 91	53.1	25.3	9.4†	15.7†	352	329	256
5	3 Jan 92	25.9	17.4	7.1†	13.0†	170	110	140
6	23 Jan 92	54.6	22.9	12.2†	15.4†	999	1059	1009
7	16 Feb 92	39.4	12.9	3.8†	6.3†	340	240	314
8	19 Feb 92	25.4	12.1	0.6†	5.3†	24	10	14
9	24 Feb 92	25.4	12.3	2.2†	7.0†	127	54	80
10	6 Mar 92	33.0	14.0	1.0†	7.6†	55	22	54
11	7 Mar 92	19.1	11.6	4.8†	8.5†	437	371	603
Total		328.0	146.3	48.4	81.2	3060	2622	2531
Mean		29.8	13.3	4.4‡	7.4‡	278	238§	230‡

* Numbers are means of two replicates.

† Different from the control treatment at P = 0.10 for the same storm.

‡ and § Different from the control treatment at P = 0.05 and P = 0.1, respectively, using paired-comparison t-test.

The extended observations made between 9 March and 22 April of 1992 (126 to 163 days after application, fig. 3) indicated that runoff volumes from the gypsum and PAM treatments were less than from the control treatment. Total runoff in this period was reduced by approximately 70% for gypsum and 35% for PAM. The Duncan's test showed runoff volumes from both treatments were significantly less than from the control for all five storms except for the second last storm for the PAM treatment (P = 0.1). These results suggest surface application of gypsum and PAM be useful in preventing clay dispersion, reducing seal/crust formation, and increasing water infiltration for soils with low EC, low ESP, and a predominant 1:1 clay mineralogy.

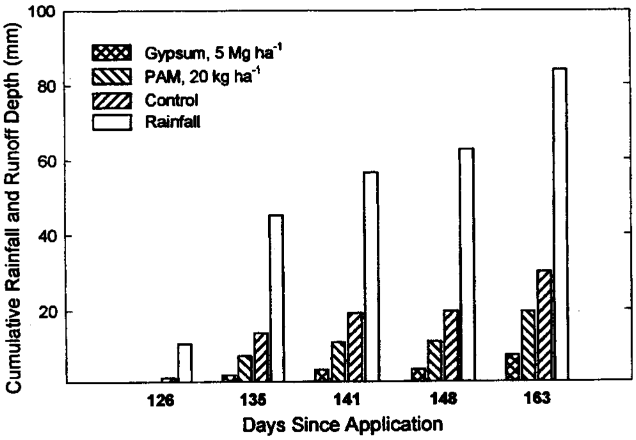

Figure 3–Cumulative rainfall and runoff during the extended period of the study (10 March to 22 April 1992) for the control, gypsum, and PAM treatments.

Anionic PAM amendment was reported to reduce runoff in earlier studies (Shainberg et al., 1990; Levy et al., 1991; Levy et al., 1992; Lentz et al., 1992), but the effectiveness was found to decline rapidly within two to four weeks in most studies. Terry and Nelson (1986) reported PAM increased infiltration significantly throughout a two-month experiment during which approximately 400 mm depth of water was flood-irrigated. Since polymers are irreversibly adsorbed to the outer surfaces of soil aggregates or soil grains (Nadler et al., 1992; Letey, 1994), the persistence of PAM amendment depended upon the behavior of the polymer nets surrounding the soil aggregates. Declining effectiveness may reflect progressive failure of polymer nets probably due to the effects of drying and wetting cycles, freezing and thawing cycles, and microbial decomposition. The longer persistence of PAM benefits observed in this study might be attributed to a low microbial activity and a lesser impact of these cycles in the winter season at the location. The persistence of PAM effects should be further studied under broader conditions to better understand the mechanisms and varying responses.

Beneficial effects of gypsum application on reducing clay dispersion and seal formation result from the elevated ionic strength in soil solution and increased Ca^{2+}-fraction on exchange sites. Miller et al. (1990) showed chemical composition of exchangeable cations was more closely related to the clay behavior (dispersion/flocculation) than was soil solution composition. When Ca^{2+} dominated exchange sites, clay dispersion was suppressed, compared with other commonly encountered cations in this soil (about 20% exchangeable magnesium, 10% exchangeable potassium, and 1-2% exchangeable sodium). The electrolyte concentration in surface runoff from observation 11 at the end of the second period was about 12.5 $mol_c\ m^{-3}$, which was greater than the critical flocculation concentration of about 5 to 6 $mol_c\ m^{-3}$ needed for clay flocculation for this soil when soil ESP was below 1% (Miller et al., 1990). The elevated electrolyte concentration prevented clay dispersion and therefore reduced seal formation. This explains why gypsum treatment was effective in reducing runoff during the period of the study.

Soil losses tended to be reduced by the gypsum and PAM treatments, but these reductions were statistically significant for only the first two observations for the PAM treatment (table 2). Compared with runoff reduction, gypsum and PAM were less effective in reducing interrill soil loss. This could be due to the offsetting effects of these treatments on erosion processes. Gypsum and PAM reduced sediment transport capacity of runoff by increasing infiltration. On the other hand, more available loose materials on the less sealed surface can increase soil loss, and this may offset the positive effects of the gypsum and PAM treatments. This could explain why soil loss was not reduced significantly as was runoff (figs. 2a and 2b).

Levy et al. (1991) conducted a field study in which PAM solution was sprayed onto the soil surface at a 20 kg ha^{-1} rate. Soil losses from the PAM treated plots were significantly less than from the control treatment under bare soil conditions for the first four sprinkler-irrigated events. Significant reduction of soil loss for events immediately following PAM application was also reported by Fox and Bryan (1992) and Zhang and Miller (1996a). These results were consistent with the findings of this study, in which soil losses from the first two storms were reduced significantly (table 2). However, the paired-comparison t-test showed that soil loss rates were overall reduced at the $P = 0.05$ level for the PAM treatments, and at $P = 0.1$ for the gypsum treatment (table 2). These test results, as a supplement to the single event tests, further revealed that these treatments were effective overall in reducing soil loss and runoff.

CONCLUSIONS

As indicated by runoff generation, screen cover, tillage, gypsum, and PAM reduced and delayed seal-crust formation. Low energy of raindrop impact was sufficient to cause seal formation on this soil. One layer of screen cover did not significantly reduce total runoff due to gradual seal formation, but it reduced total soil loss by 70% as compared to the control due to dissipation of raindrop impact energy that reduced splash detachment and raindrop impact-induced sediment transport. Periodic disruption of crusts by raking reduced total runoff by 32%, but the effectiveness tended to decrease with an increase in storm size. Gypsum and PAM reduced total runoff by 67% and 44% relative to the control. Soil loss, compared with runoff reduction, was reduced in a lesser degree probably because reduced surface sealing might have increased soil detachability. These results, combined with the previous study (Zhang and Miller, 1996b), indicate that a combination of physical and chemical treatments might be the best approach for controlling surface sealing, runoff, and erosion on soils with low EC, low ESP, and predominant 1:1 clay mineralogy.

Gypsum and PAM reduced runoff significantly in the five months following surface application ($P = 0.1$). This result showed a high potential for using gypsum and PAM to control runoff and erosion under similar conditions. The persistent effects observed for gypsum and PAM might have been enhanced by low-intensity rains and a possible slower microbial activity during the winter season at the study site. Therefore, the persistent effects should be further evaluated under different climatic and soil conditions.

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