POLYACRYLAMIDE SOIL AMENDMENT EFFECTS ON RUNOFF AND SEDIMENT YIELD ON STEEP SLOPES:

PART I. SIMULATED RAINFALL CONDITIONS

D. C. Flanagan, K. Chaudhari, L. D. Norton

ABSTRACT. *Steep slopes consisting of disturbed soil are very often found in construction, landfill, and surface mining situations. Although legislation and economics dictate that vegetative cover be established on these slopes as rapidly as possible, the occurrence of large rainfall events during critical periods of vegetation establishment can frequently cause extensive soil loss. Sediment generated from erosion can impair off–site water quality, and on–site damages to the eroded region can be so extensive that expensive earthmoving, regrading, reseeding, and remulching may be necessary. We evaluated the effectiveness of two soil treatments for reducing runoff and soil loss from a silt loam topsoil placed on a constructed 32% slope. The three treatments were an untreated control, 80 kg* ha^{-1} *anionic polyacrylamide (PAM) applied as a liquid spray, and 80 kg* ha^{-1} *PAM as a liquid spray combined with a dry granular application of 5 Mg* ha^{-1} *of gypsum. Replicated plots were subjected to a range of rainfall intensities under a programmable rainfall simulator, and resulting runoff and sediment loss were measured. In the first event of 69 mm* h^{-1} *uniform rainfall applied for one hour to initially dry soil, the PAM and PAM with gypsum treatments significantly reduced runoff by almost 90% and sediment yield by 99%, compared to the control. Total runoff through a series of simulated rainfall events was reduced by 40% to 52%, and sediment loss was reduced by 83% to 91% for the plots treated with PAM and PAM plus gypsum, respectively. These results indicate that the use of PAM alone or in combination with gypsum can significantly reduce runoff and soil loss from large storm events, and may be a cost–effective approach to protect the soil during critical periods of vegetation establishment, particularly for disturbed soils on steep slopes.*

Keywords. *Soil erosion, Erosion control, Soil amendments, Polymers, Polyacrylamide, PAM.*

Many of the agricultural production lands within the U.S. are on relatively low slopes (0% to 25%) that in certain circumstances can have significant soil erosion problems. However, steeper slopes (>25%), which are typical of agricultural production in many regions of the world as well as on many forested regions and construction sites within the U.S., can experience extreme soil loss. High erosion rates may be attributed to combinations of the high slope gradients and bare, loose soil conditions after tillage, logging, or construction activities.

Construction of highways, landfills, aboveground reservoirs, etc., often involves creation of embankments having very steep slopes (3:1 to 2:1 is typical) formed from totally disturbed soil stripped from other locations. Grass or other vegetation is usually seeded almost immediately after embankments are formed, so that the vegetation can grow and stabilize the slope, providing permanent protection from erosion. Mulches (such as wheat straw, woodchips, etc.) are often applied at the time of seeding to protect the soil until the grass is well established.

Unfortunately, mulches have several disadvantages and are not always effective at controlling soil erosion. Problems with mulching include high application costs, flammability, bulk, unsightliness, and unavailability (Wallace and Wallace, 1986a). Several soil erosion studies have shown that surface mulch loses effectiveness at reducing soil loss once runoff and rilling occurs below the mulch layer (Meyer et al., 1972; Kramer and Meyer, 1969; Foster et al., 1982a).

One alternative or complementary way to control erosion during the critical period of vegetation establishment is through the use of soil surface amendments. In particular, the application of synthetic organic polymers known as polyacrylamides (PAM) has been shown in previous studies to reduce soil surface sealing, increase infiltration, decrease runoff, maintain soil aggregate stability, and decrease soil erosion. Most previous experiments with PAM have been conducted on relatively low–gradient agricultural slopes (Gabriels et al., 1973; Fox and Bryan, 1992; Zhang and Miller, 1996; Mitchell et al., 1996; Flanagan et al., 1997a, 1997b).

Soil surface amendments for erosion control are most often used to attempt to reduce the amount of aggregate breakdown and soil surface sealing that can result when fine

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silts and dispersed clays from destroyed aggregates are washed into the soil pore space. Seal formation occurs at the soil surface from breakdown of surface clods and aggregates due to physical and chemical mechanisms (Agassi et al., 1981). Rainfall impact energy breaks soil aggregates at the surface and compacts the disaggregated particles into a thin and very dense seal (Agassi and Ben–Hur, 1992). Chemical dispersion of the soil depends on the exchangeable sodium percentage of the soil and electrolyte concentration of applied water (Agassi et al., 1981), and when chemical dispersion occurs, clay migrates into the soil pores, resulting in a thickened and reinforced seal (Agassi and Ben–Hur, 1992). Surface seals form into a thin layer (<2 mm) on the soil surface and are characterized by a greater density, higher shear strength, smaller pores, and a much lower saturated hydraulic conductivity than the underlying soil (Shainberg and Levy, 1994). Soil sealing has a detrimental effect on soil properties, causing reduced infiltration rates, increased runoff and soil erosion rates, and interference with seed germination (Bradford et al., 1987; Shainberg and Levy, 1994).

Polymers interact mainly with the clay fraction of soils, and the degree of interaction depends on the properties of both the soil and the polymer (Seybold, 1994). Important polymer properties are the type and amount of surface charge, polymer configuration, molecular weight, and molecular size (Theng, 1982). Important soil properties are the type and amount of clay, the soil solution ionic strength, the type of ions in solution, and pH.

Anionic polyacrylamide has been found to be the most effective type of polymer in controlling seal formation and enhancing infiltration and seed emergence (Shainberg and Levy, 1994; Wallace and Wallace, 1986b). Additionally, anionic PAM was found to have longer residual effects in controlling soil loss than cationic PAM (Levy et al., 1992).

Anionic polymers are commonly adsorbed to the soil through cationic bridges between the polymer and soil anionic groups. Multivalent cations in solution bridge the negatively charged soil constituents and polymers together (Laird, 1997). The effectiveness of anionic polymers is enhanced when the soil clay is maintained in a flocculated state (Shainberg and Levy, 1994), which can be accomplished through addition of multivalent cations at the soil surface. In recent studies examining the use of PAM soil amendments, multivalent cation concentrations at the soil surface have been increased through surface–applied gypsum (Shainberg et al., 1990; Zhang and Miller, 1996) or gypsiferous by–products from coal–fired electrical power plants (Norton et al., 1993; Flanagan et al., 1997a, 1997b).

Mitchell et al. (1996) sprayed a solution of anionic PAM at a rate of 18 kg ha^{-1} on 3% slope field plots subject to natural rainfall conditions, but found no significant effect of the PAM treatment on runoff volume and sediment yield. They suggested that greater application rates might be needed for the PAM to be effective. Fox and Bryan (1992) studied the effectiveness of an anionic PAM soil conditioner on runoff and soil loss on low–slope field plots under natural and simulated rainfall conditions. A liquid solution of PAM applied at rate of 25 kg ha^{-1} from a perforated pail onto disturbed soil was effective in reducing runoff and soil loss. They concluded that PAM application could provide useful temporary reductions in sheet and rill erosion, and could be effectively combined with grass seeding for permanent reclamation. Gabriels et al. (1973) conducted laboratory studies on small plots at 9% slope under simulated rainfall and found that anionic PAM applied at 38 kg ha^{-1} was effective in reducing runoff and soil loss rates. In laboratory studies on small plots at 58% slopes, Wallace and Wallace (1986a) applied PAM at rates ranging from 16 to 161 kg ha^{-1}. They observed that soil loss rates decreased with increasing rates of PAM application. Flanagan et al. (1997a, 1997b) applied anionic polyacrylamide at a rate of 20 kg ha^{-1} to pre–formed rills on a silt loam soil at 6% to 9% slopes in a field rainfall simulator study. The PAM significantly reduced sediment discharge from the rills, even at inflow water rates up to 60 L min^{-1}.

Shainberg et al. (1990) studied the interaction between PAM and electrolyte concentration at the soil surface in clayey soils on 5% slopes. Treatments studied were PAM application at rates of up to 40 kg ha^{-1} alone and with 5 Mg ha^{-1} of phosphogypsum. PAM was much more effective on clayey soil in reducing runoff rates when applied with phosphogypsum. Stern et al. (1991) studied the effect of phosphogypsum and PAM applications on runoff volume under natural rainfall conditions on loamy soils in small plots. PAM was applied at 20 kg ha^{-1} and in combination with phosphogypsum at 5 Mg ha^{-1}. The PAM and phosphogypsum combined treatment resulted in less runoff than either the control or phosphogypsum alone treatments.

The objective of this study was to evaluate the effects of PAM and gypsum soil amendment treatments on runoff and sediment yield under controlled conditions in the field. A rainfall simulation study was conducted on a disturbed soil in large (3 m × 9 m) plots on a steep slope. The main hypothesis was that PAM and PAM combined with gypsum amendments would reduce runoff and soil loss compared to the control. A companion study examined the effectiveness of the same soil amendment treatments combined with vegetation seeding on steep slopes under natural rainfall conditions (see Part II).

MATERIALS AND METHODS

The study was conducted at a Vulcan Materials, Inc., aggregate pit in West Lafayette, Indiana, from June to August 1998. A fill slope was constructed at a 32% gradient using local sand and gravel material to form the subgrade for the study plots on 22 to 26 June. Topsoil, which had been stripped and stockpiled previously during aggregate mining operations, was spread on 30 June to 2 July at a depth of about 30 cm over the sand and gravel subgrade to form the surface for the erosion plots.

The effect of the soil amendment treatments PAM (P), PAM plus gypsum (PG), and an untreated control (C) on runoff and sediment yield was studied in a randomized complete block design experiment with three replicates of each treatment. Nine erosion plots were constructed that were 2.96 m wide × 9.14 m long, with the major axis aligned parallel to the maximum slope gradient. The perimeter of each plot was bordered with 20 cm high sheet metal to delineate runoff and soil from plot surroundings. A metal collection trough at the bottom of the plots directed all runoff to a collection spout for sampling. After the plots were constructed, they were covered with plastic sheets to protect the surface from rainfall and to maintain uniform initial soil moisture.

Table 1. Physical and chemical properties of the soil used in the experiment.

Soil Property	
Texture	Silt Loam
Clay content (%)	18
Silt content (%)	61
Sand content (%)	21
pH	6.62
Organic matter (%)	2.94
CEC (cmole$_c$ kg^{-1})	17.75
Ca (cmole$_c$ kg^{-1})	9.34
Mg (cmole$_c$ kg^{-1})	2.94
K (cmole$_c$ kg^{-1})	0.37
Na (cmole$_c$ kg^{-1})	0.0

Final plot preparations were made the day preceding each rainfall simulation experiment. The same worker rototilled the plots to a depth of 25 cm and uniform surface consistency, and the plots were then raked lightly to raise the elevation slightly at plot lateral boundaries to ensure runoff containment. Plots were then surveyed by differential leveling to determine slope gradient. Bulk soil samples to a depth of 10 cm were taken for chemical and physical analysis. For the P and PG treated plots, antecedent moisture samples were taken prior to applying the PAM and gypsum treatments. Antecedent moisture samples for the C treated plots were taken immediately preceding the rainfall simulation experiment. Properties of the surface soil are provided in table 1.

Three soil amendment treatments were tested: 80 kg ha^{-1} of anionic PAM applied as a liquid solution (P), 80 kg ha^{-1} of anionic PAM as a liquid solution and a dry application of 5 Mg ha^{-1} of commercial gypsum (PG), and a control (C) with no soil amendments applied. Treatments were replicated three times. The PAM used in this study was a commercially available product, Percol 336 (100% active solids) manufactured by Ciba Specialty Chemicals (Suffolk, Va.). The PAM was anionic, with a charge density of 32% and having a very high molecular mass of 20 Mg mol^{-1}. The polymer granules were dissolved in deionized water to produce a 0.25% solution (whole product basis), and this was prepared in 150 L batches, using a drum stirrer driven by a drill press. The PAM solution was applied to the plots using a specially constructed sprayer. A 2.2 kW motor powered a roller pump, which sprayed the PAM solution through 30 m of rubber hose and a spray wand with an 8006 nozzle tip. To apply the PAM at the rate of 80 kg ha^{-1}, 86.4 L of the solution were sprayed on each plot, equivalent to a 3 mm depth of wetting. The PAM solution was applied to dry soil, and following application, the soil surface was allowed to dry for 24 hours prior to rainfall simulation.

The commercial gypsum, manufactured by the U.S. Gypsum Company (Chicago, Ill.), applied in this study had a manufacturer's assay of 83% minimum calcium sulfate as $CaSO_4 \cdot 2H_2O$, a minimum 19.3% Ca equivalent, and a minimum 15.4% S equivalent.

Rainfall was applied with a programmable rainfall simulator (fig. 1) designed by Foster et al. (1982b) for use in agricultural field studies on gently sloping sites. This simulator was modified to accommodate slopes as high as 50% for erosion studies on construction site slopes (Fan, 1988) through the use of wedges to keep simulator troughs level and a modified supporting frame that could be adapted to varying slope steepness. Full coverage of the plot length required seven rainfall simulator troughs positioned across the plots at 1.52 m spacing. Adjusting the sweep cycle time and/or the time interval between sweeps of the oscillating spray nozzles varies rainfall intensity with this simulator.

Figure 1. Programmable rainfall simulator used in the field experiment set up for testing and calibration.

Rainfall intensity of the simulated storm is proportional to the frequency of nozzle oscillation. Calibration runs were conducted at the site (fig. 1) to determine the frequency of nozzle sweeps required to achieve each of the three rainfall intensities used in this study. A programmable logic controller that controls the frequency of nozzle oscillations was programmed to allow instantaneous change in rainfall intensity by turning a switch. The simulator used 80100 VeeJet spray nozzles (Spraying Systems Co., Wheaton, Ill.) at 41.4 kPa water pressure and 2.44 m height above the soil surface. The drop size distribution and impact velocity of the simulated rainfall with this nozzle configuration results in a kinetic energy of about 75% of natural rainfall in a 64 mm h^{-1} event, which is considered sufficient for comparative studies (Meyer and McCune, 1958). Deionized water, with a maximum electrical conductivity (EC) of 40 μS cm^{-1}, was used to approximate the electrolyte level of natural rainfall.

Rainfall was applied in a series of three consecutive events: a dry run, followed by a wet run, and a very wet run. The dry run was conducted on initial field soil conditions, with rainfall applied at a target intensity of 64 mm h^{-1} for one–hour duration. One hour after the end of the dry run, the wet run was conducted at a target intensity of 64 mm h^{-1} for one–hour duration. Thirty minutes following the wet run, a 45–minute very wet run was conducted at three different rainfall intensities. The first 15 minutes of the very wet run had a target intensity of 64 mm h^{-1}, followed by 15 minutes at 28 mm h^{-1}, followed by 15 minutes at 100 mm h^{-1}. The dry run corresponds with a storm having a return period of 25 years for west–central Indiana. A cumulative rainfall depth of 128 mm over three hours at the end of the wet run approximates a rainfall event having a return period exceeding 100 years. The target cumulative rainfall depth at the end of the very wet run, 176 mm over 4.25 hours, also represents a rainfall event having a return period exceeding 100 years (Huff and Angel, 1992). The simulated rainfall applications to the experiment plots began on 25 July and were completed on 20 August 1998.

Following initiation of runoff, timed samples (approximately 15 to 30 seconds) were taken in an appropriate size container (depending on runoff rate) at intervals not exceeding 3 minutes. When the runoff rate was low, samples were collected in 1 L plastic bottles, and as the runoff rate increased larger plastic pails were used. The electrical conductivity of the runoff sample was measured immediately in the field with a portable field EC meter. Runoff samples collected in 1 L bottles were returned to the laboratory and used to determine both runoff rate and sediment concentration. Runoff volume was determined gravimetrically, and sediment concentration was determined by flocculating the sediment with alum and oven–drying the samples to constant mass at 105° C. Runoff volume for samples collected in pails was determined by weighing the mass of water at the field site with a portable electronic balance.

Once the runoff rate had increased to levels requiring collection in pails, sediment concentration sampling was continued in 1 L plastic bottles. Two replicate samples were taken from the plot collection trough outflow at intervals not exceeding 3 minutes. Sediment concentration was determined as described previously. The two replicate samples

Table 2. Comparison of total runoff and sediment yield between treatments.

Simulation Run	Treatment	Total Runoff (mm)	Reduction of Runoff Compared to Control (%)	Total Sediment Yield (Mg ha^{-1})	Reduction of Sediment Yield Compared to Control (%)
Dry	C	41.5 a[a]		76.3 a[a]	
	P	5.9 b	86	1.0 b	99
	PG	4.7 b	89	0.7 b	99
Wet	C	60.0 a		71.5 a	
	P	44.2 b	26	11.3 b	84
	PG	35.0 b	42	8.8 b	88
Very wet (64 mm h^{-1})	C	13.5 a		11.3 a	
	P	10.6 ab	22	3.4 b	70
	PG	8.3 b	39	2.2 b	81
Very wet (28 mm h^{-1})	C	6.8 a		3.1 a	
	P	5.9 a	13	1.0 b	69
	PG	3.9 b	43	0.4 b	85
Very wet (100 mm h^{-1})	C	26.7 a		48.3 a	
	P	23.1 b	14	18.4 ab	62
	PG	19.2 c	28	7.2 b	85
Very wet subruns combined	C	46.9 a		62.6 a	
	P	39.6 b	16	22.7 b	64
	PG	31.3 c	33	9.9 b	84
Dry + wet	C	101.5 a		147.8 a	
	P	50.2 b	51	12.3 b	92
	PG	39.7 b	61	9.5 b	94
Dry + wet + all very wet	C	148.4 a		210.4 a	
	P	89.7 b	40	35.0 b	83
	PG	71.0 b	52	19.3 b	91

[a] When followed by the same letter, runoff depth and sediment yield for a given run are not significantly different at $P < 0.05$ using paired t–tests for multiple means comparisons.

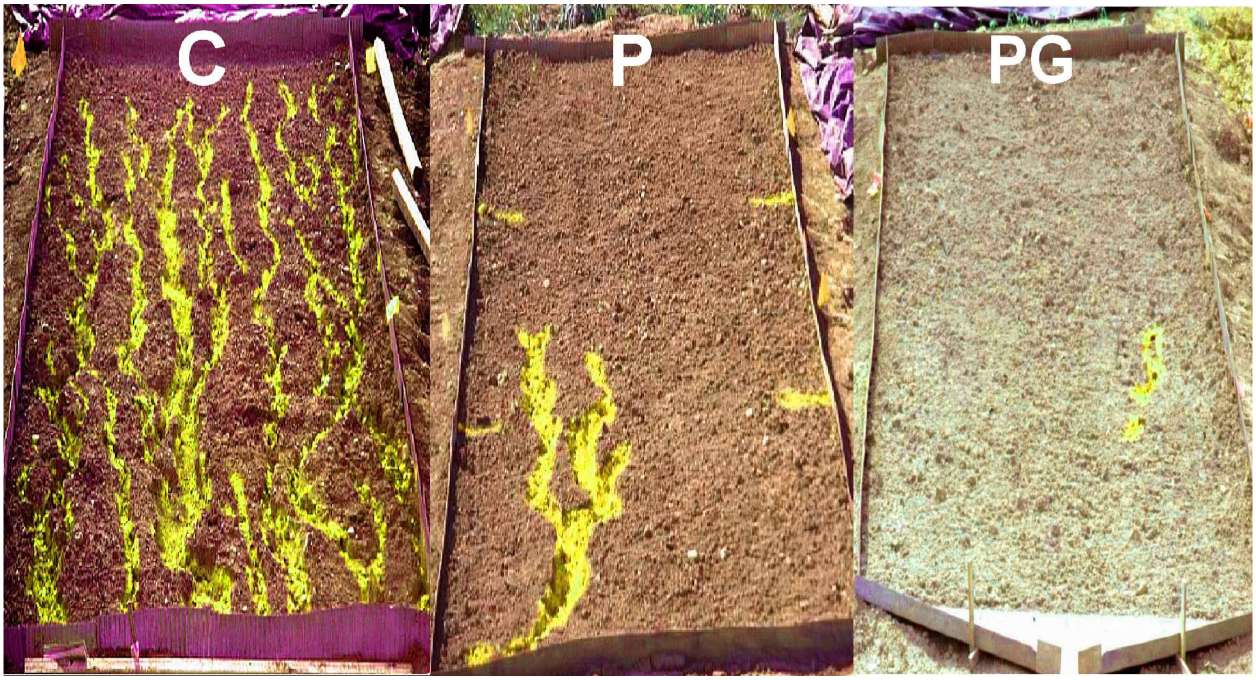

Figure 2. Representative plot conditions after completion of entire sequence of rainfall applications. The rills were painted and image hue modified for greater clarity. Soil amendment treatments were (left to right): control (C), PAM (P), and PAM and gypsum (PG).

were averaged to determine the average sediment concentration in the runoff at the time of sampling.

Following all rainfall simulations, the plots were allowed to dry, and then soil samples (top 5 cm) from each plot were collected and used to determine the effectiveness of the amendment treatments in improving soil surface conditions in laboratory tests of aggregate stability using wet sieving (Kemper and Rosenau, 1986). Surface clod samples were also collected and used to determine the crust bulk density with a liquid Saran procedure (Blake and Hartge, 1986).

Analysis of variance and comparison of means were used to determine if runoff and sediment loss differences between treatments were statistically significant. Analyses were conducted on individual run and cumulative values for runoff volume, runoff rate, sediment concentration, sediment discharge rate, and total sediment loss. Separation of mean responses for the three treatments was conducted using paired t tests at a significance level of $P < 0.05$.

RESULTS AND DISCUSSION

The P and PG treatments were extremely effective at significantly reducing both runoff and soil loss (table 2). In the initial simulation runs on initially dry soil, total sediment losses for the P and PG treatments were both only about 1 Mg ha^{-1}, a reduction of 99% compared to the 76 Mg ha^{-1} of soil loss from the control treatment. Soil loss reductions were maintained throughout all rainfall simulation events, and average overall reductions were 83% for the P treatments and 91% for the PG treatment. Rilling was virtually eliminated on the treated plots, as can be seen in figure 2.

Actual average rainfall depths measured were 69 mm for the dry run, 72 mm for the wet run, and 56 mm for the very wet run, for a total applied rainfall depth of 197 mm over the 4.25–hour experiment period. In the laboratory tests conducted on soil crust samples obtained after the experimental plots had dried, soil aggregate stability was found to be significantly greater and crust bulk density was significantly lower for the P and PG treatments, compared to the C.

A large reason for the reduced sediment loss for the P and PG plots was a very large reduction in runoff due to the soil amendment treatments. For the runs on initially dry soil, mean runoff depth was significantly reduced from 41.5 mm for the control to 5.9 mm for the P treatment and 4.7 mm for the PG treatment (table 2). Throughout the series of simulated rainfall events, the effect of the amendments on reducing runoff decreased as the soil pore space became filled with water and the initially loose soil surface consolidated. In addition, even though the soil amendments were very effective in reducing aggregate breakdown and clay dispersion, some aggregate destruction did occur on the treated soil. The magnitude of the runoff reduction was thus decreased in the wet and very wet runs.

Measurements of the runoff water electrical conductivity during the rainfall simulations showed that the PG treatment was persistent in increasing EC to very high levels (from about 1000 μS cm^{-1} in the initial dry runs, to 250–525 μS cm^{-1} in the very wet runs) through the 197 mm of cumulative rainfall for the entire experiment. Visual inspection of the plots after the final rainfall simulation also found gypsum particles present in the soil just below the surface. Since gypsum was still present, it is likely that increased EC in subsequent rainfall events could provide continued benefits.

RAINFALL SIMULATIONS ON INITIAL FIELD CONDITIONS (DRY RUNS)

Figure 3 shows the effect of the soil amendment treatments on runoff rate, sediment concentration, and sediment yield rate as a function of cumulative rainfall depth in the runs on initially dry soil (average of 3 replications). Runoff from the control plots began very early, after only about 5 mm of rainfall had been applied, and runoff rate

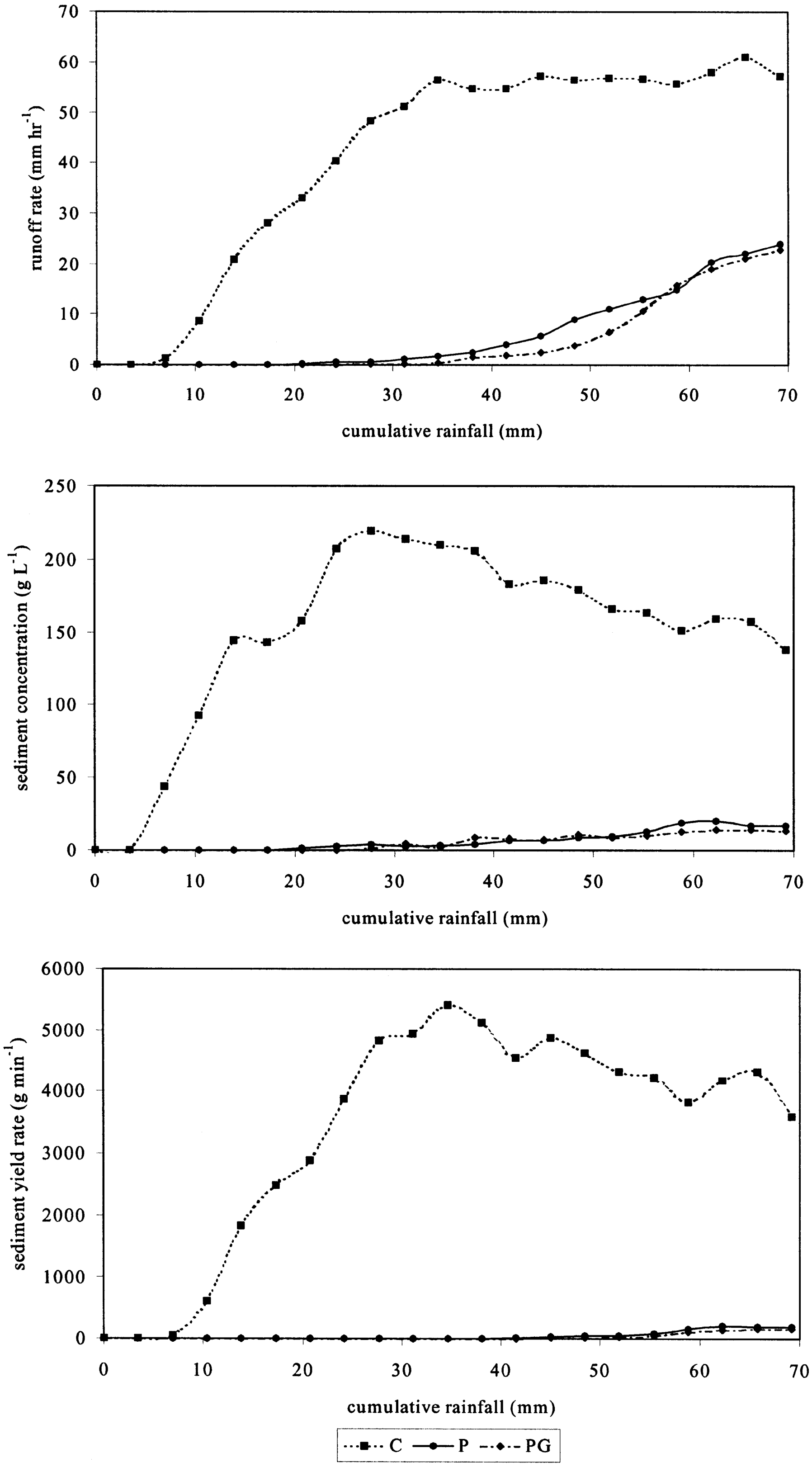

Figure 3. Runoff rate, sediment concentration, and sediment yield rate versus cumulative rainfall for the runs on initial field soil conditions (dry runs) (average of three replications). Uniform rainfall applied at a target intensity of 64 mm h^{-1}.

rapidly increased to a high steady–state value of about 55 mm h^{-1} (table 3). Runoff began later on the P treated plots at about 20 mm of cumulative rainfall, and much later on the PG treated plots at about 35 mm of cumulative rainfall, and both P and PG approached a rate of about 23 mm h^{-1} at the end of the dry run (table 3), although steady state was not achieved

Table 3. Comparison of runoff rate, sediment concentration, and sediment yield rate between treatments by run.

		Final Runoff Rate		Final Sediment Concentration		Final Sediment Yield Rate	
Run	Treatment	mm h^{-1}	% reduction of control	g L^{-1}	% reduction of control	g min^{-1}	% reduction of control
Dry	C	55.3 a[a]		138 a[a]		3600 a[a]	
	P	23.9 b	57	21.1 b	85	229 b	94
	PG	22.9 ab	59	14.5 b	90	163 b	96
Wet	C	60.1 a		96.3 a		2680 a	
	P	54.8 a	9	35.6 b	63	893 b	67
	PG	45.0 a	25	31.0 b	68	609 b	77
Very wet (64 mm h^{-1})	C	59.3 a		79.5 a		2230 a	
	P	54.5 ab	8	37.5 b	53	885 b	60
	PG	46.2 b	22	24.7 b	69	516 b	77
Very wet (28 mm h^{-1})	C	22.0 a		34.6 a		364 a	
	P	22.7 a	–3	11.5 b	67	113 b	69
	PG	12.9 b	41	7.3 b	79	41.3 b	89
Very wet (100 mm h^{-1})	C	107 a		160 a		8110 a	
	P	106 a	1	87.2 ab	45	4290 ab	47
	PG	89.8 a	16	38.8 b	76	1580 b	81

[a] When followed by the same letter, runoff rate, sediment concentration, and sediment yield rate values for a given run are not significantly different at $P < 0.05$ using paired t–tests for multiple means comparison.

(fig. 3). The rapid runoff on the control plots was due to extensive and rapid aggregate breakdown and associated surface sealing, with the fine silt and clay particles from the slaked aggregates filling and clogging soil pores. The P and PG treatments substantially reduced aggregate destruction and clay dispersion, which kept soil pores open and infiltration rates high.

Sediment concentration on the control plots increased very rapidly to a peak of about 220 g L^{-1} at 30 mm of cumulative rainfall, and then sediment concentration decreased gradually to about 140 g L^{-1} at the end of the dry run (fig. 3, table 3). This increase then decrease was associated with the rapid initiation and development of an extensive rill network during the beginning of the dry run. Before rill initiation, rainfall impact energy caused surface aggregate breakdown, resulting in an abundance of easily transported sediment particles. As the rill channels formed and extended across the entire C plots, sediment concentrations rapidly increased with the flush of loose surface particles and newly detached sediment from rill headcuts, and then decreased as the soil surface stabilized. For the P and PG treated plots, sediment concentrations were extremely low and slowly approached about 20 g L^{-1} (table 3).

Sediment yield rates for the control increased rapidly to very high values of about 5000 g min^{-1} at 30 mm of cumulative rainfall and then slowly decreased to a final rate of about 3600 g min^{-1} (table 3). Rates for the P and PG treatments were extremely low and slowly approached values of about 200 g min^{-1}.

Rainfall Simulations on Wet Soil (Wet Runs)

Figure 4 shows the runoff rates, sediment concentration, and sediment discharge rates versus cumulative rainfall for the second in the sequence of rainfall simulations. Runoff began almost immediately for all treatments, due to the wet soil conditions from the previous storm event. Steady–state runoff was rapidly achieved on the control plots, with a constant runoff rate of about 60 mm h^{-1} (table 3). Runoff rates for the P and PG treatments remained below those for the control and did not approach steady state until very late in the wet run. Final runoff rate for the P treatment was 55 mm h^{-1} and for the PG treatment was 45 mm h^{-1}.

Sediment concentration on the control plots increased rapidly to about 130 g L^{-1} and then slowly decreased to about 100 g L^{-1} at the end of the simulation run (table 3). For the P and PG treatments, sediment concentration remained at very low values and slowly approached 30 g L^{-1} towards the end of the run.

An ANOVA of final sediment yield rates for the wet run showed major significant differences between treatments. The rates for the control rapidly increased to about 3500 g min^{-1}, remained there for most of the run, and then decreased to a final rate of about 2700 g min^{-1} (table 3). Sediment yield rates for the P and PG treatments slowly increased through the run to about 900 g min^{-1} and 600 g min^{-1}, respectively. The P and PG final rate values were both significantly less than the control but were not significantly different from each other.

The continued low runoff and sediment loss from the P and PG treatments showed continuing effectiveness of the soil amendments at maintaining aggregate stability and reducing surface sealing and soil detachment.

Rainfall Simulations on Very Wet Soil (Very Wet Runs)

For the very wet soil, three target rainfall intensities were applied in a sequence of 15 minutes each at 64, 28, and 100 mm h^{-1}. Throughout this run, the same trends that were observed in the simulations on dry and wet soil were observed, namely that the control treatment resulted in the greatest values for runoff rate, sediment concentration, and sediment yield rate (table 3, fig. 5). In addition, the PG treatment consistently showed the lowest values, and the P treatment fell between the C and PG.

The runoff rate observed for the PG treatment at the 28 mm h^{-1} rainfall rate was 13 mm h^{-1}, which was significantly less than that for either the C (22 mm h^{-1}) or P (23 mm h^{-1}) treatments. Total runoff for the PG treatment from the 28 and 100 mm h^{-1} rainfall intensities was significantly less than either the C or P treatments, indicating

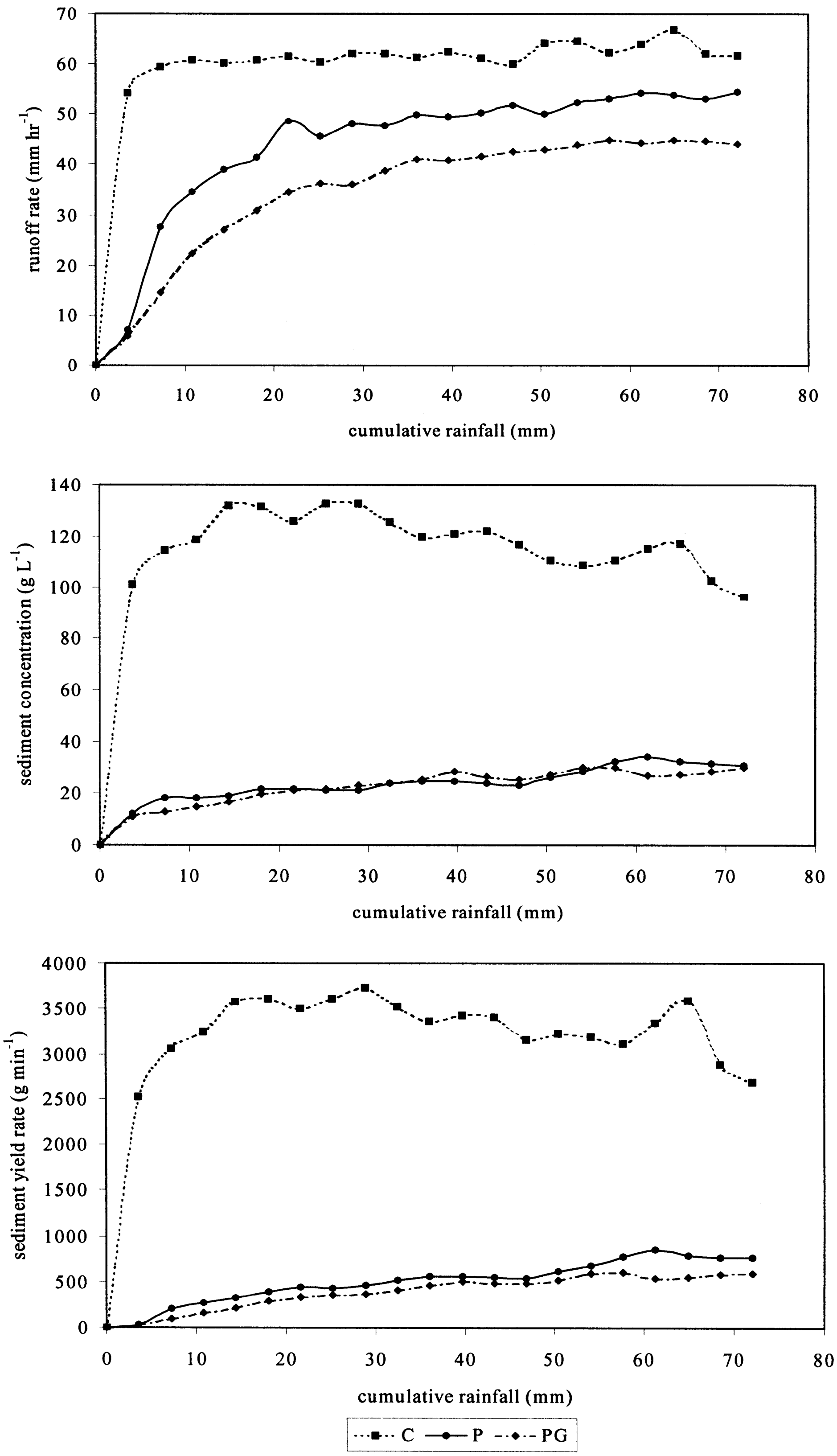

Figure 4. Runoff rate, sediment concentration, and sediment yield rate versus cumulative rainfall for the runs on wet soil (average of three replications). Uniform rainfall applied at a target intensity of 64 mm h^{-1}.

an additional benefit from the use of the gypsum in terms of runoff reduction. However, there were no significant differences between the P and PG treatments in terms of sediment concentration or total sediment yield for any of the rainfall intensities in the very wet run, or for any other run in the experiment. Variability in the sediment data in the experiment likely masked any differences between the P and PG treatments.

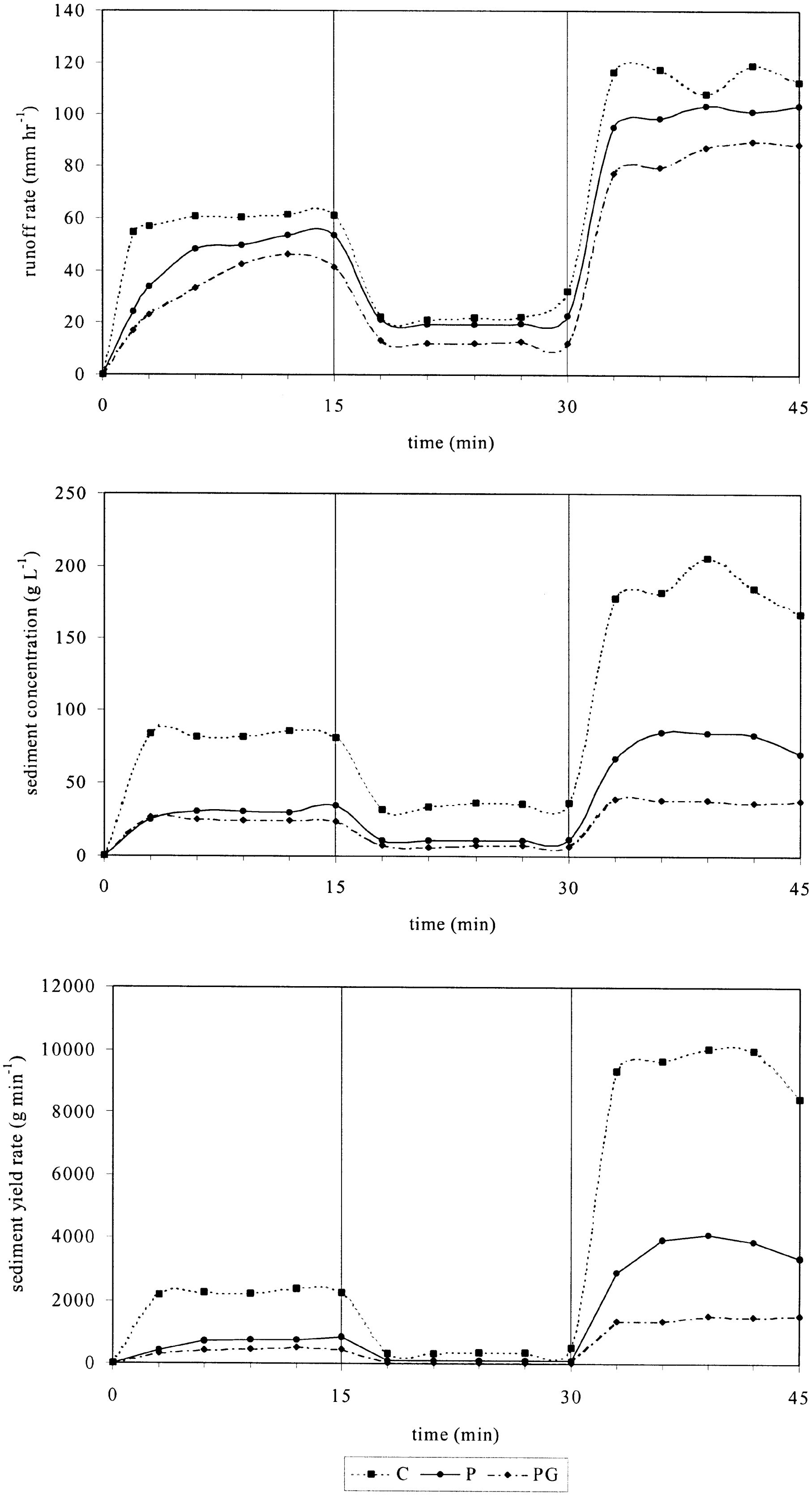

Figure 5. Runoff rate, sediment concentration, and sediment yield rate versus time for the runs on very wet soil (average of three replications). Rainfall intensity target rates were varied from 64 to 28 to 100 mm h^{-1} at 15–minute intervals.

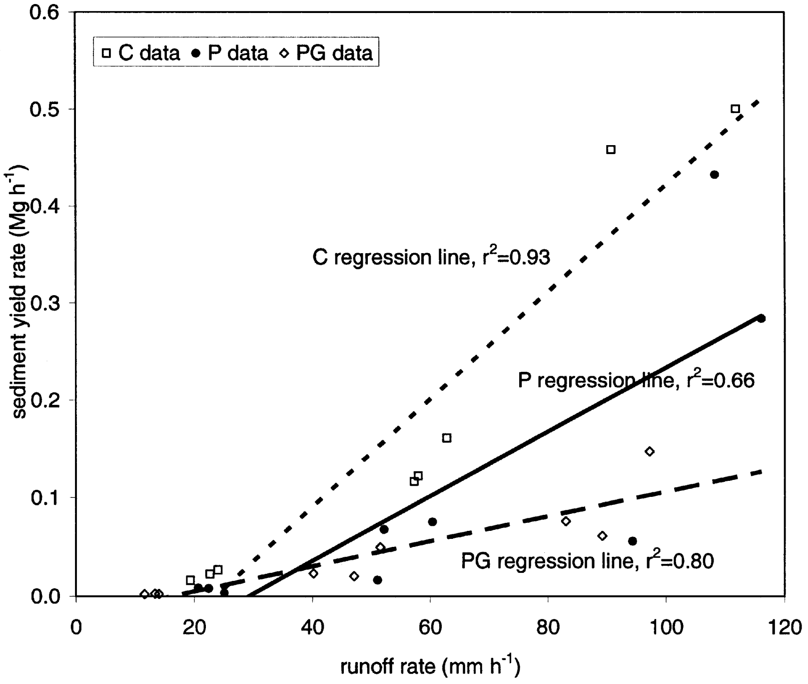

Figure 6. Sediment yield rate versus runoff rate using data from the runs on very wet soil.

The average steady–state sediment yield rate and runoff rate data from the very wet runs are plotted in figure 6, along with linear regression lines for each of the three treatments. These results show that sediment yield increased as a function of runoff rate, which is a measure of erosive force (Huang and Bradford, 1993). The slopes of the regression lines for all three treatments were found to be significantly different from each other at the $P < 0.05$ level. The "effective" soil erodibility was thus greatest for the C treatment, medium for the P treatment, and least for the PG treatment. Flanagan et al. (1997b) found similar results of decreased erodibility in soil treated with PAM compared to a control.

Figure 2 shows three representative plots from the rainfall simulator experiment following all storm events. The control plot on the left side of the image is deeply rilled from left to right and from top to bottom. If this area were on a roadside, then extensive and costly regrading and reseeding probably would be necessary. The PAM treated plot in the center of the image has only one major rill at the bottom that extends about halfway up the plot. On the PG plot, shown on the right side of the image, essentially no rilling is visible, even after 197 mm of rainfall was applied in 4.25 hours on this 32% slope.

SUMMARY

The PAM (P) and PAM and gypsum (PG) treatments resulted in significant reductions in runoff and sediment yield compared to the control (C) through the series of rainfall simulations. Total runoff through all the rainfall simulations was reduced by 40% and 52% respectively, in the P and PG treatments, compared to the C. Total sediment yield in the P and PG treatments was reduced by 83% and 91%, respectively, through the series of rainfall events. The P and PG treatments had the greatest impact in reducing runoff and sediment yield in the first rainfall event, a storm with a return period of 25 years (69 mm event over a one–hour duration in west–central Indiana). In the rainfall simulations on initially dry soil, the P and PG treatments reduced runoff by almost 90%, and sediment yield was reduced by 99%, compared to the control. The beneficial effects of the P and PG treatments in reducing runoff and sediment yield were persistent through cumulative rainfall events corresponding with a return period exceeding 100 years (197 mm rainfall over a 4.25–hour duration in west–central Indiana).

Reduced runoff and soil loss in the P and PG treatments was attributed to improved surface conditions on these plots. The P and PG treatments were effective in maintaining a well–aggregated soil surface that was resistant to surface sealing. In contrast, soil aggregates disintegrated quickly and dispersed particles caused rapid surface seal development in the control plots. Aggregate stability was greater and crust bulk density was lower in soil samples obtained following the rainfall simulations on the P and PG plots, compared to the control.

A well–defined network of rills developed quickly in the C treatments and was well established in all the C plots by the end of the dry run. In the P and PG plots, when rills did develop, the extent of rill formation was minor. Since rill development is associated with increased sediment yield, this feature may account for substantially increased soil loss from the C treatment, compared to the P and PG.

Analysis of results from the very wet run indicated that erodibility was decreased in the P and PG treatments compared to the C. Sediment yield rate in the P and PG treatments was reduced compared to the C under the same levels of erosive force, as represented by the runoff rate. The trend in reduced sediment yield in the P and PG treatments was consistent over the range of runoff rates resulting from the very wet run rainfall simulations.

Gypsum amendments applied in conjunction with PAM in the PG treatments resulted in additional benefits compared to

PAM applied alone. In the very wet runs, total runoff was significantly lower for the PG treatments compared to either the P or C. Regression analysis of sediment yield rate versus runoff rate showed that the slope of the sediment yield line was significantly reduced in the PG treatment compared to P alone. The natural electrolyte concentration of the soil was low enough that increasing multivalent cation levels with concurrent gypsum application with PAM in the PG treatment reduced clay dispersion and improved the effectiveness of the PAM amendment, compared to PAM applied alone in the P treatment. The PG treatment was persistent in increasing runoff EC through 197 mm of cumulative rainfall. Since gypsum remained in the soil following the series of rainfall simulations, it is possible that increased EC in subsequent rainfall events could result in continued beneficial effects.

The results from this study support earlier research documenting the dominant influence of rill formation on soil erosion (Foster et al., 1984; Lattanzi et al., 1974). A well–developed rill network formed in the C treatment, with only minor rilling in the P and PG treatments. The development of rills in the C treatments corresponded with total soil loss through the series of rainfall simulations of 210 Mg ha^{-1}, compared to 35 Mg ha^{-1} and 19 Mg ha^{-1} in the P and PG treatments, respectively. Conventionally applied erosion control measures for steep slopes have been identified as being ineffective in controlling rill erosion and having high application costs. The cost of a PG treatment at the rates used in this study was about \$580 ha^{-1}, which is roughly 15% of the estimated cost of grass seeding with straw mulching (\$3780 ha^{-1}). PAM soil amendments, which were very effective in controlling soil erosion and controlling rill development in this study, warrant consideration as an alternative or supplementary erosion control method to conventional techniques.

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