POLYACRYLAMIDE SOIL AMENDMENT EFFECTS ON RUNOFF AND SEDIMENT YIELD ON STEEP SLOPES: PART II. NATURAL RAINFALL CONDITIONS

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ABSTRACT. *Soil loss from embankments at highway construction sites, sanitary landfills, and elsewhere can be extremely large due to the loosened state of the soil and very steep slope gradients (typically 2:1 to 3:1). Soil amendments have the potential to protect the soil during critical periods of vegetation establishment, thus reducing on–site damages and costs as well as reducing off–site impacts on water quality. In Part I of this study, results from a rainfall simulator experiment showed that use of an anionic polyacrylamide (PAM) could significantly reduce runoff and soil loss under the extreme condition of a large rainfall event occurring immediately after PAM application. In this part of the study, the same soil amendment treatments were tested in field situations on steep slopes under natural rainfall, to determine PAM effectiveness for typical constructed embankment conditions. One experiment was conducted on a highway cutslope on a clay loam subsoil placed at a 35% slope. The second experiment was in a surface sanitary landfill on a filled silt loam topsoil placed at a 45% slope, typical of a landfill cap. The soil amendment treatments used were an untreated control, an application of 80 kg ha^{-1} anionic polyacrylamide (PAM) as a liquid spray, and 80 kg ha^{-1} PAM applied as a liquid spray combined with a dry granular application of 5 Mg ha^{-1} of gypsum. A barrel collection system was used to measure total runoff volume and sediment loss. Total soil loss over all events at the two experiment sites for plots treated with PAM was reduced in the range of 40% to 54%, compared to the control. The addition of gypsum had a significant effect on runoff volume only on the silt loam soil, possibly due to higher rainfall at that site and/or to the presence of substantial amounts of calcium in the clay loam subsoil at the other location. PAM and PAM with gypsum increased grass establishment and growth on treated plots compared to the control. These results indicate that the use of anionic polyacrylamide (with or without gypsum) can provide substantial benefits in reducing runoff and soil loss, and enhancing vegetation growth on very steep embankments.*

Keywords. *Soil erosion, Erosion control, Soil amendments, Polymers, Polyacrylamide, PAM, Vegetation establishment, Reclamation, Construction sites.*

Construction sites and other locations with disturbed soil are very susceptible to soil erosion, especially during the critical period before vegetation has become well established. Lack of vegetal cover coupled with high slope gradients and lengths combine to leave these sites extremely vulnerable to soil loss. Soil erosion on these steep slopes can lead to time–consuming and costly repairs, including reshaping of soil and revegetation of eroded slopes. In addition to the direct local consequences of erosion, the off–site impacts include non–point source pollution, which encompasses problems associated with downstream transport of sediment, nutrients, pesticides, and other harmful chemicals.

The breakdown of surface clods and aggregates during rainfall events creates a seal at the soil surface, causing reduced water infiltration and increased soil erosion (McIntyre, 1958). Formation of a seal during rainfall and the crust resulting from the dried seal have been attributed to physical and chemical mechanisms (Agassi et al., 1981). Impact energy from raindrops causes disintegration of soil aggregates at the surface and compaction of disaggregated particles into a thin and very dense seal (Agassi and Ben–Hur, 1992). Dispersion of the soil due to chemical mechanisms depends on the exchangeable sodium percentage (ESP) of the soil and the electrolyte concentration of the applied water (Agassi et al., 1981). The electrolyte content of natural rainfall is sufficiently low to cause clay dispersion in many soils. When this dispersion occurs, clay particles migrate into soil pores, creating a thickened and reinforced seal (Agassi and Ben–Hur, 1992). Surface seals form a thin layer (<2 mm) on the soil surface and have increased bulk density, higher shear strength, finer pores, and lower permeability than the original soil (McIntyre, 1958; Bradford et al., 1987). Soil sealing has a negative impact on soil properties, causing reductions in infiltration and increases in runoff and soil loss (Bradford et al., 1987). Seedling emergence can also be reduced (Cook and Nelson, 1986; Rubio et al., 1989).

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The physical and chemical processes leading to soil sealing and crust formation can be controlled to achieve reductions in runoff and soil erosion. Mulches applied at the soil surface reduce the physical impact energy of rainfall, consequently reducing sealing (Agassi et al., 1985). Soil conditioners applied to the soil surface chemically strengthen the bonds between primary particles comprising soil aggregates, resulting in decreased aggregate disintegration (Ben–Hur and Letey, 1989). Chemical dispersion of clay particles can be reduced by introducing electrolyte sources (multivalent cations, such as Ca^{++}) at the soil surface (Agassi et al., 1981).

A conventional method to reduce soil erosion and promote vegetal establishment is the application of mulch on the soil surface (INDOT, 1995; Shainberg and Levy, 1994). Conventionally used mulching materials include plant residues, gravel, rock fragments, and woodchips (Agassi and Ben–Hur, 1992). Mulches reduce soil erosion by absorbing rainfall impact and reducing seal formation, leading to increased infiltration and reduced runoff (Lattanzi et al., 1974; Mannering and Meyer, 1963). Mulches also reduce overland flow velocity and maintain moisture to protect soil and promote grass establishment during critical periods. Although the benefits of mulch application in reducing soil erosion and promoting vegetation growth are well accepted, several studies have noted weaknesses in surface mulch treatments on steep slopes.

Meyer et al. (1972) evaluated the effect of straw, stone, gravel, woodchip, and Portland cement mulches on erosion of a 20% slope sandy loam subsoil in a rainfall simulation experiment. Although straw mulch reduced soil loss compared to the untreated control, it was noted that for this treatment the main source of eroded soil was shallow rills that developed beneath the mulch. Once serious rilling occurred beneath the straw mulch, so that bare soil was exposed to runoff, mulch rate did not appreciably affect erosion rates. Loss of surface mulch effectiveness in reducing soil erosion once rilling or runoff occurred under the mulch layer was also noted in other studies (Foster et al., 1982; Kramer and Meyer, 1969). Meyer et al. (1970) evaluated the effect of straw mulch rates ranging from 0.6 to 9 t ha^{-1} on a loam soil at 15% slope under simulated rainfall. They found that even the lowest rates of mulch resulted in significant reductions in soil loss compared to the control, but concluded that straw mulch rates of at least several metric tons per hectare would be required for reducing soil erosion on sites prone to serious erosion problems.

Lack of effectiveness in controlling erosion once rilling occurs and the requirement for high mulch application rates are the primary limitations of conventional mulching methods. Other problems associated with mulches include a detrimental effect on plant growth due to low soil temperatures and excessive moisture retention under heavy mulching, lack of availability, flammability, bulk, unsightliness, and high application costs. Due to limitations associated with conventional mulching practices, new erosion control methods are needed for disturbed sites to minimize soil erosion and attain acceptable probability of revegetation, especially where conventional practices, such as straw mulching, are costly or inadequate (Meyer et al., 1972).

An alternative practice to mulching soils is modification of soil properties by applying chemical amendments to the soil. Many recent studies have shown that the use of synthetic organic polymers, such as polyacrylamide (PAM), as surface soil amendments results in benefits including reduction of runoff volumes, decrease in sediment yield, and stabilization of soil structure (Seybold, 1994). Studies have also shown that PAM soil amendments can be successful in improving seedling emergence rates in grass and other plant species (Cook and Nelson, 1986; Rubio et al. 1989).

In greenhouse studies, Rubio et al. (1989) found that grass species emergence was improved with the addition of PAM soil amendments. In their evaluation of PAM application rates of 0, 0.2, 2.0, 20.0, and 200.0 kg ha^{-1}, the best emergence rates were achieved with application rates of 20 and 200 kg ha^{-1}. The improved germination rates were attributed to the PAM treatment's ability to reduce the surface crusting of soil after rainfall events. Cook and Nelson (1986) conducted seedling emergence studies of sweet corn and alfalfa on a loam soil under greenhouse and field conditions. Application of anionic PAM solution to the soil surface resulted in improved seedling emergence and reduction in soil surface sealing through several irrigation events. They suggested optimal PAM application rates of 45 to 67 kg ha^{-1} for row crops planted on low slopes. Helalia and Letey (1989) conducted pot studies to test the effectiveness of several polymeric soil conditioners on increasing seedling emergence of tomatoes. Their results indicated that anionic PAM was the most effective of the polymers tested.

The objective of this study was to evaluate the effects of PAM and gypsum soil amendment treatments on runoff, sediment yield, and vegetation establishment in field erosion plot studies under natural rainfall conditions. The experiments were conducted on disturbed soils on steep slopes at two different sites. The persistence of treatment effect was evaluated by conducting the study over rainfall events through several months of the growing season. The hypothesis of the study was that PAM and PAM combined with gypsum amendments would reduce runoff and soil loss and improve vegetation establishment compared to the control.

Materials and Methods

Studies were conducted at two sites, one in 1997 at an Indiana Department of Transportation (INDOT) highway project, and another in 1998 at a Waste Management, Inc., recycle disposal facility (RDF) site, both located near Logansport, Indiana. The INDOT study, conducted on a slope known locally as the Cotner cut, is referred to as the Cotner study, and the 1998 study is referred to as the RDF study.

The treatments studied were the soil amendments PAM (P), PAM and gypsum (PG), and an untreated control (C). Three replicate plots of each treatment were constructed at each of the Cotner and RDF sites. The experimental plots were arranged in a completely randomized design at the Cotner site, and in randomized complete block design at the RDF site. The randomized complete block design at the RDF site was used to account for any possible block effects due to the influence of surrounding forest vegetation, and to separate any potential block effects from treatment effects.

The Cotner study site was a cutslope created during highway construction. The original surface horizon was removed by scrapers during grading and removed from the construction zone. Once the road excavation was completed, newly exposed subsoil was spread over the cutslope area to

Figure 1. Typical plot setup for the natural rainfall studies, showing the two–barrel runoff collection system.

provide the new surface soil for the embankment. The subsoil was spread over the slope surface at a 25 cm depth with a bulldozer. The RDF site was a fillslope constructed for the purpose of this study. A large sloping berm was constructed from clay excavated on site, which is used locally as landfill cell–lining material. Topsoil was stripped from an adjacent area and placed on the slope by scrapers, and then spread at a 60 cm depth with a bulldozer. The method used to construct this slope followed the normal procedure used by the landfill operators for reclaiming disturbed land.

The runoff collection plots 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, soil, and vegetation from plot surroundings. At the downslope end of the plot, a metal collection trough directed all plot runoff to the runoff collection system (fig. 1). Runoff from the plots was collected using a two–barrel system. The runoff was directed into the first of two 230 L plastic barrels. Once the first barrel filled with runoff and sediment, a flow divisor diverted 1/9 of the overflow from the first barrel to the second barrel, and the remaining 8/9 of the overflow was discharged to a drainage channel. The runoff collection system used in this study has been described previously by Mitchell et al. (1996).

The surface soil on the plots was tilled by a hand pick to a uniform depth and consistency by the same worker. The soil at the Cotner site was tilled to a depth of about 4 cm, and clods were broken until the maximum aggregate diameter was less than 4 cm. The RDF soil was tilled similarly, but tillage was to a depth of about 5 cm. After tillage, the plots were raked lightly to raise the elevation slightly at plot lateral boundaries to ensure containment of runoff within the plot. Plots were then surveyed by differential leveling to determine plot slope. Plot slopes at the Cotner and RDF sites were 35% and 45%, respectively.

To ensure consistent initial conditions in the replicated plots, application of the amendments (and thus the start of the observation period) was conducted with the soil in a dry antecedent condition, with an anticipated 24–hour period of dry weather following to allow complete drying. Immediately prior to application of amendment treatments, soil samples were taken for physical and chemical analysis, and for antecedent moisture determination. Soil properties for both sites are shown in table 1.

All surface amendments were uniformly distributed in each study plot. Fertilizer (12–12–12) was hand broadcast on the plots at 900 kg ha^{-1}. The seed mix used was INDOT Type R, a mix of Kentucky Fescue, perennial rye grass, and Jasper Red Fescue, applied at 190 kg ha^{-1}.

The PAM was commercially available Percol 336, manufactured by Ciba Specialty Chemicals (Suffolk, Va.). The PAM was anionic, with a 32% charge density and molecular mass of 20 Mg mol^{-1} (formulation had 100% active solids). The PAM solution applied in the field experiments was prepared in 150 L batches by dissolving it in deionized water to produce a 0.25% solution (whole product basis) and then 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

Table 1. Physical and chemical properties of the soils at the experiment sites.

Soil Property	Cotner Site	RDF Site
Texture	Clay loam	Silt loam
Sand content (%)	22.0	21.4
Silt content (%)	49.5	60.9
Clay content (%)	28.5	17.7
pH	7.68	7.40
Organic matter (%)	1.23	1.63
CEC (cmole$_c$ kg^{-1})	34.86	22.34
Ca (cmole$_c$ kg^{-1})	29.80	18.83
Mg (cmole$_c$ kg^{-1})	4.65	2.99
K (cmole$_c$ kg^{-1})	0.27	0.45
Na (cmole$_c$ kg^{-1})	0.14	0.08

of rubber hose and a spray wand with an 8006 nozzle tip. The PAM was applied at a rate of 80 kg ha^{-1}, which required spraying 86.4 L of solution on each treated plot (3 mm depth).

A commercial gypsum product manufactured by the U.S. Gypsum Company (Chicago, Ill.) was used in this study. The manufacturer's assay indicated 83% minimum calcium sulfate as $CaSO_4 \cdot 2H_2O$, minimum 19.3% Ca equivalent, and minimum 15.4% S equivalent. Gypsum was hand broadcast immediately following PAM application, at a rate of 5 Mg ha^{-1}.

Runoff volume and sediment yield for each plot were determined for runoff–producing storm events. For each event, runoff was either limited to the volume of the first collection barrel, or for larger events, both collection barrels contained runoff. A 20 L bucket was placed within the first barrel to facilitate collection for very small events.

When the runoff volume for a plot was less than 20 L, the runoff volume was determined gravimetrically. For sediment yield determination, the sediment was flocculated with alum, decanted, dried to a constant mass at 105° C, and weighed. For events where runoff exceeded the 20 L volume of the small bucket but did not overflow the first collection barrel, runoff volume was determined by measuring the depth of runoff in the barrel. Prior to establishing the plots, each runoff collection barrel had been calibrated to provide a depth versus volume relationship. Two 1 L replicate samples were taken for sediment concentration determination by sampling the well–stirred contents of the barrel. Sediment concentration samples were weighed, flocculated with alum, decanted, dried to constant mass at 105° C, and reweighed. Sediment yield for each plot was determined by multiplying the sediment concentration by the runoff volume.

During large runoff events, the runoff volume exceeded the capacity of the first collection barrel, and runoff overflowed into the second collection barrel. In these events, the heavier sediments settled quickly in the first barrel, and the lighter sediment particles maintained in suspension were transported into the second barrel. Storm events having runoff volumes large enough to overflow into the second collection barrel often resulted in heavy sediment loads in the first collection barrel. Obtaining a representative sediment concentration sample from the first barrel using the method described previously and used for lower–runoff events was not always appropriate, since large sediment loads limited the ability to take a representative concentration sample. When large runoff volumes resulted in heavy sediment loads in the first barrel, an alternative method was used to determine sediment yield. The entire contents (water and sediment) of the first barrel were transferred to another barrel. The sediment was flocculated with alum, and the supernatant water was decanted. The mass of the water–sediment mixture was measured in the field using a large–capacity portable scale. The resulting water–sediment mixture was stirred into a viscous sludge in the barrel using an electric drill and drum stirring attachment. Two replicate 1 L samples of the sludge were taken, weighed, dried to constant mass at 105° C, and reweighed to obtain the sludge moisture content. The increased viscosity of the sludge allowed more accurate sampling for determining moisture content. The mass of dry sediment in the first barrel was determined by adjusting the mass of the wet sludge for the moisture content, as determined from the sludge moisture samples.

Runoff volume in the second collection barrel was determined from the predetermined depth versus volume relationship. When runoff overflowed into the second barrel, the total plot runoff volume equaled the sum of the runoff volume from the first barrel and nine times the runoff volume of the second barrel. The sediment concentration and sediment yield in the second barrel were determined by taking two 1 L replicate samples from the well–stirred contents of the barrel. Sediment concentration samples were weighed, flocculated with alum, decanted, dried to constant mass at 105° C, and reweighed. When runoff overflowed into the second barrel, the total plot sediment yield equaled the sum of the sediment yield from the first barrel and nine times the sediment yield of the second barrel.

Vegetation establishment was evaluated at regular intervals during the study period by observing entire plots and photographing plots for future reference. Vegetation establishment was documented at regular intervals, usually coinciding with runoff producing storm events, but occasionally more often when required during rapid growth stages. At specific observation dates, each of the nine plots was ranked from one (best) to nine (worst) for establishment of vegetation. Vegetation rankings were based on density, vigor, and homogeneity of growth. Direct plant count measurements or plant sampling on the plots were not performed in order to prevent disturbance that might impact the runoff and sediment loss results.

Results and Discussion

Data Analysis

Statistical analysis was conducted using analysis of variance (ANOVA) procedures to determine if runoff volume and sediment yield differences between treatments were statistically significant (SAS, 1990). Analyses were conducted for each runoff–producing event and for cumulative response over the observation period. On some occasions, data for one or more plots could not be collected due to collection barrels being overturned during storm events. At the Cotner site, some data was unavailable for the events of 13 August, 17 August, and 11 September 1997, and a corresponding reduction in the degrees of freedom in the ANOVA was made for treatment estimates based on available data. Similar adjustments were made in the ANOVA for the RDF site for some unavailable data for events of 30 May, 15 June, 23 July, 27 August, 10 September, and 16 November 1998. Separation of mean responses for the three treatments was conducted using the least significant difference (LSD) method at a significance level of $P < 0.05$.

Cumulative vegetation establishment comparisons for the entire observation period were made for each site by ranking the combined records of vegetation establishment for each site by plot. The cumulative record was divided into representative classes of vegetation establishment. At the Cotner site, 17 sets of photos were used in the analysis. A set was composed of photographs of each of the nine plots taken on a single observation day (3 each of C, P, and PG). Each set of photos was ranked on a scale from 1 to 9 (1 = best, 9 = worst) on the quality of vegetation on the day of observation, based on photographs and accompanying field notes. Next, the slides for all 17 events were ranked from 1 to 153 (153 = 17 photo events × 9 plots), while maintaining consistency with the rankings already established for each observation day. To clarify, during the ranking of the 153 slides, the relative rankings established for plots on each single observation day were not contradicted. Next, the 153 slides (in continuous ranked order) were classified into ten classes of vegetal growth, without effort to evenly distribute the number of slides in each class (i.e., the ten classes did not have equal numbers of slides). To check, the beginning and end slide of each class were compared to judge if they belonged in the same class. Then, the median–numbered slide for each class was pulled as representative of the class, and these ten slides were observed to ensure integrity of the classification process. The average ranked values for each treatment on each date and overall were reported. A similar procedure was followed for the RDF site, although in that case there were only six observation dates for a total of 54 slides.

At the Cotner site, installation of the plots and application of the treatments was completed in June 1997, and runoff and sediment yield data were collected until September 1997. Total rainfall over the study period was 214 mm, with nine runoff–producing rainfall events. Plots at the RDF site were established in May 1998 and were monitored until November 1998. Total rainfall over the study period was 688 mm, with 17 runoff–producing rainfall events. Event and cumulative runoff and sediment yield data for the Cotner and RDF sites are presented in tables 2 and 3, respectively. Graphs of cumulative runoff depth and cumulative sediment yield for the Cotner study are plotted in figures 2 and 3, and graphs of cumulative runoff depth and cumulative sediment yield for the RDF site are plotted in figures 4 and 5, respectively. Vegetation establishment ratings for the Cotner and RDF sites are shown in tables 4 and 5, respectively.

RUNOFF

At the Cotner site, the P treatment significantly reduced runoff compared to C in five of the nine storm events (table 2). Runoff reduction for these five events ranged from 25% to 91% compared to C. The PG treatment produced significant reductions in runoff compared to C in the same five storm events as the P treatment, with reductions ranging from 36% to 90%. Event runoff depths and cumulative runoff for the P and PG treatments were not significantly different from each other. The cumulative runoff for the study period was significantly reduced by an average of 33% for the P and PG treatments compared to the C. Figure 2 shows the treatment effects on runoff depth over the entire amount of cumulative natural rainfall for the experiment, which has trends similar to the rainfall simulator part of this study (Part I, fig. 3).

Table 2. Cotner site: Event and cumulative runoff and sediment yield results.

Event Date	Rainfall Depth (mm)	Treatment	Runoff Depth (mm)	Reduction of Runoff Compared to Control (%)	Sediment Yield (Mg ha^{-1})	Reduction of Sediment Yield Compared to Control (%)
19 July 1997	10.6	C	0.4 a[a]		0.3 a[a]	
		P	0.1 b	81	0.0 b	100
		PG	0.1 b	84	0.0 b	100
21 July 1997	12.8	C	4.5 a		8.6 a	
		P	0.4 b	91	0.1 b	98
		PG	0.5 b	90	0.2 b	97
22 July 1997	38.3	C	23.1 a		38.3 a	
		P	19.7 a	15	14.4 b	62
		PG	15.8 a	32	14.5 b	62
13 Aug 1997	41.3	C	26.6 a		48.1 a	
		P	16.1 a	39	25.1 b	48
		PG	20.5 a	23	31.1 b	35
15 Aug 1997	5.6	C	1.3 a		1.6 a	
		P	0.5 b	60	0.3 b	82
		PG	0.6 b	52	0.4 ab	73
17 Aug 1997	35.5	C	23.2 a		30.4 a	
		P	14.0 a	40	16.9 b	44
		PG	17.5 a	25	22.6 b	26
25 Aug 1997	11.2	C	4.4 a		4.3 a	
		P	3.3 b	25	2.4 b	44
		PG	2.8 b	36	1.9 b	56
28 Aug 1997	4.3	C	1.6 a		1.8 a	
		P	1.1 b	30	0.7 b	61
		PG	1.0 b	40	0.6 b	67
11 Sept 1997	25.8	C	17.8 a		12.1 a	
		P	13.1 a	26	7.0 a	42
		PG	11.0 a	38	8.2 a	32
Total	185.4	C	102.9 a		145.4 a	
		P	68.3 b	34	66.9 b	54
		PG	69.7 b	32	79.6 b	45

[a] When followed by the same letter, runoff and sediment yield values for a given event are not significantly different at $P < 0.05$ using the LSD method.

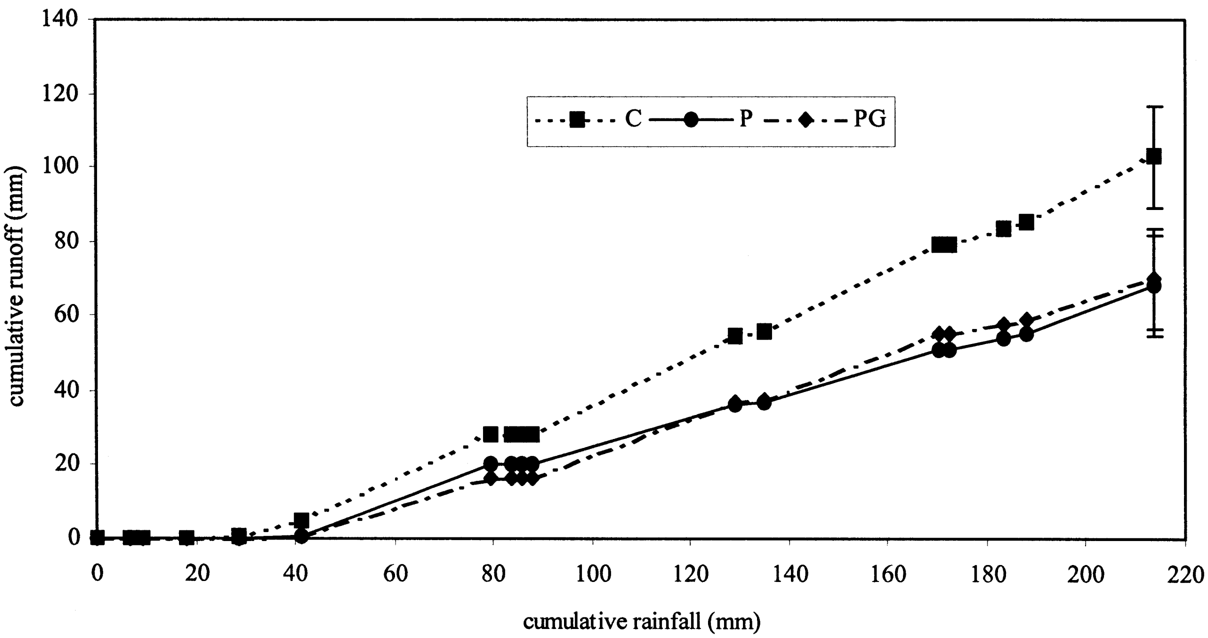

Figure 2. Cumulative runoff versus cumulative rainfall for the natural rainfall study at the Cotner site. Bars for final points indicate P < 0.05 confidence intervals.

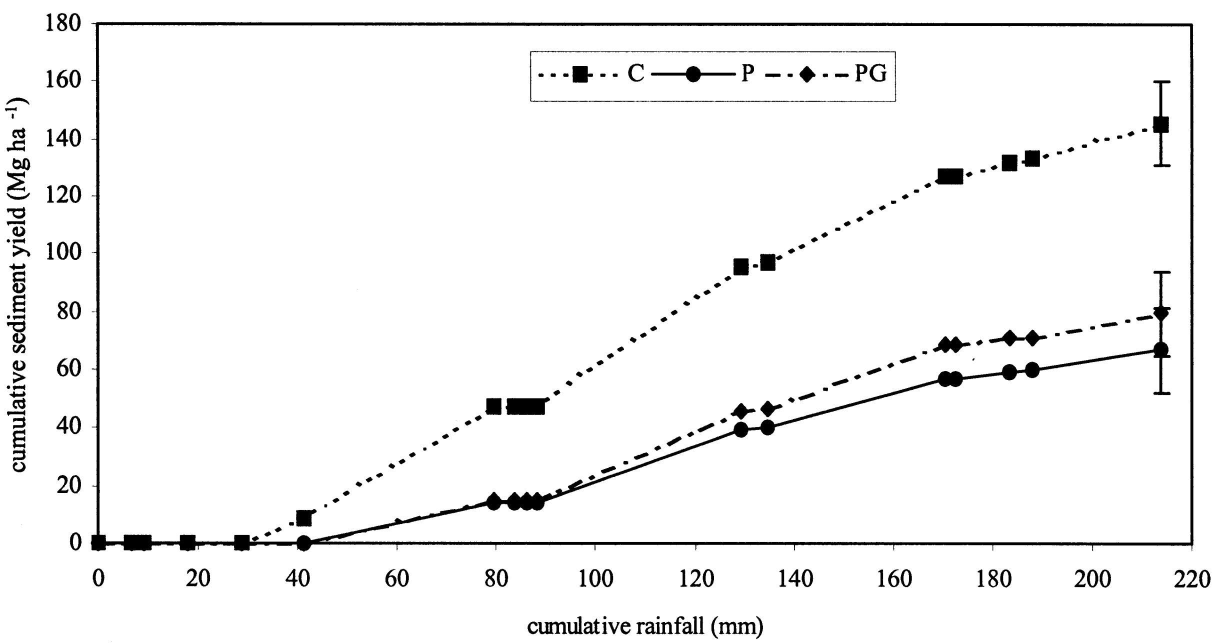

Figure 3. Cumulative sediment yield versus cumulative rainfall for the natural rainfall study at the Cotner site. Bars for final points indicate P < 0.05 confidence intervals.

At Cotner, P and PG treatments had no effect on runoff when rainfall exceeded 25 mm. The four events in which the P and PG treatments did not significantly reduce runoff were the largest rainfall events of the observation period (22 July, 13 August, 17 August, and 11 September 1997) with rainfall depth ranging from 26 to 41 mm. On 22 July 1997, lack of significant runoff reduction in the P and PG treatments was likely due to high antecedent moisture conditions from rainfall in two of the preceding three days. Similarly, the event of 17 August 1997 had 47 mm of rainfall in the preceding four days. Antecedent rainfall resulted in reduced infiltration capacity of the soil; thus, a greater proportion of subsequent rainfall later was partitioned to runoff since infiltration capacity was exhausted. Although runoff reduction was not statistically significant in the four largest rainfall events, the P and PG treatment means followed the trend of runoff reduction in comparison to C. A possible explanation for failure to statistically separate the P and PG means from C in the larger events is that in three of these events (13 August, 17 August, and 11 September 1997), data from some treatment replications were missing. Consequently, the

Table 3. RDF site: Event and cumulative runoff and sediment yield results.

Event Date	Rainfall Depth (mm)	Treatment	Runoff Depth (mm)	Reduction of Runoff Compared to Control (%)	Sediment Yield (Mg ha^{-1})	Reduction of Sediment Compared to Control (%)
30 May 1998	63.3	C	23.3 a[a]		115.8 a[a]	
		P	23.0 a	1	70.6 b	39
		PG	26.7 a	–15	62.9 b	46
12 June 1998	51.1	C	26.0 a		21.1 a	
		P	18.3 b	30	12.2 b	42
		PG	15.9 b	39	11.8 b	44
13 June 1998	10.4	C	3.1 a		0.7 a	
		P	1.9 b	39	0.4 a	50
		PG	1.1 b	63	0.4 a	50
15 June 1998	14.2	C	3.8 a		0.7 a	
		P	2.8 ab	28	0.4 b	50
		PG	1.4 b	64	0.4 b	50
17 June 1998	12.9	C	5.3 a		2.2 a	
		P	4.6 ab	13	1.1 b	50
		PG	2.9 b	45	0.7 b	67
19 June 1998	12.4	C	1.7 a		0.4 a	
		P	1.2 ab	28	0.4 a	0
		PG	0.4 b	74	0.0 b	100
30 June 1998	40.3	C	16.6 a		12.2 a	
		P	7.5 b	55	4.8 b	61
		PG	7.3 b	56	3.7 b	70
6 July 1998	49.1	C	29.2 a		34.4 a	
		P	20.6 ab	29	22.9 ab	33
		PG	15.9 b	46	14.4 b	58
8 July 1998	24.7	C	5.5 a		1.8 a	
		P	3.6 b	36	1.1 b	40
		PG	2.1 b	63	0.7 b	60
23 July 1998	120.0	C	78.7 a		19.6 a	
		P	92.5 a	–17	12.2 ab	38
		PG	73.0 a	7	3.0 b	85
4 Aug 1998	39.1	C	4.7 a		0.7 a	
		P	2.3 b	52	0.4 ab	50
		PG	1.6 b	67	0.0 b	100
5 Aug 1998	31.4	C	12.7 a		0.7 a	
		P	7.2 b	43	0.0 b	100
		PG	5.9 b	53	0.0 b	100
8 Aug 1998	23.2	C	7.6 a		0.0 a	
		P	7.1 a	6	0.0 a	–
		PG	6.4 a	15	0.0 a	–
27 Aug 1998	15.1	C	15.1 a		1.5 a	
		P	7.1 a	53	0.4 a	75
		PG	7.5 a	50	0.4 a	75
10 Sept 1998	28.1	C	6.1 a		0.4 a	
		P	2.8 a	54	0.4 a	0
		PG	3.2 b	48	0.0 b	100
8 Oct 1998	54.9	C	3.3 a		0.4 a	
		P	2.3 b	31	0.0 b	100
		PG	2.4 b	27	0.0 b	100
16 Nov 1998	45.5	C	7.5 a		0.4 a	
		P	7.5 a	0	0.0 b	100
		PG	7.5 a	0	0.0 b	100
Total	635.7	C	250.2 a		212.3 a	
		P	212.1 a	15	127.6 b	40
		PG	181.2 b	28	99.1 b	53

[a] When followed by the same letter, runoff and sediment yield values for a given event are not significantly different at $P < 0.05$ using the LSD method.

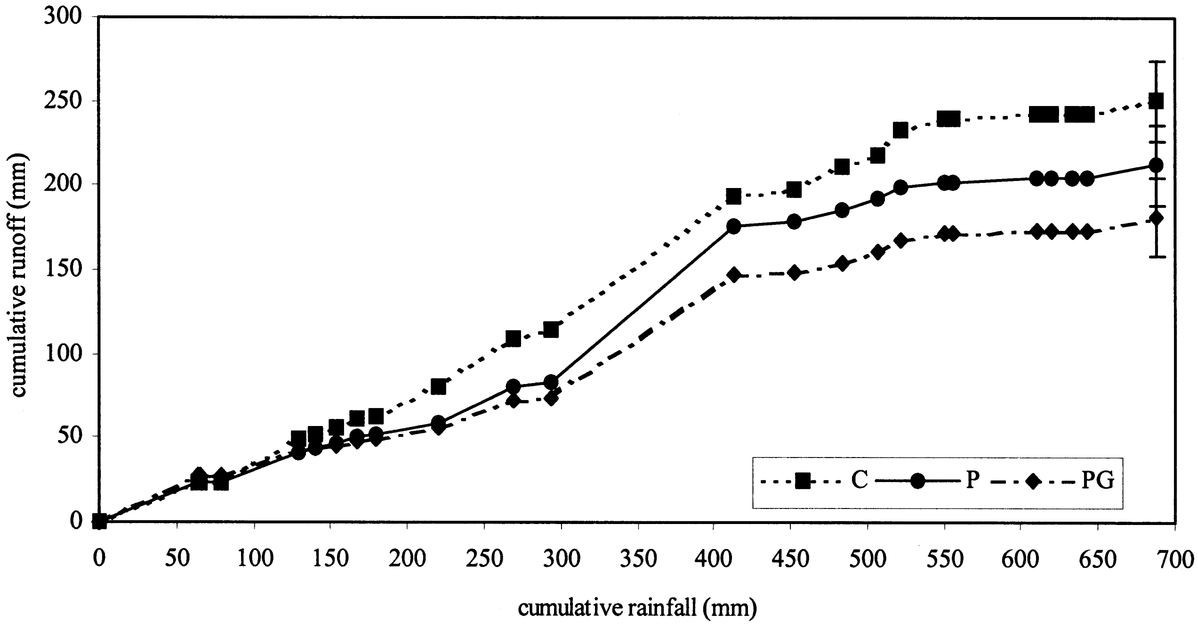

Figure 4. Cumulative runoff versus cumulative rainfall for the natural rainfall study at the RDF site. Bars for final points indicate P < 0.05 confidence intervals.

ANOVA procedure resulted in greater variance and less statistical separation of means.

At the RDF site, the P treatment significantly reduced runoff by 30% to 55% compared to C in seven of the storm events (table 3). The PG treatment significantly reduced runoff compared to C in 12 storm events, with runoff reductions from 27% to 74%. Runoff depths for the P and PG treatments did not differ in any of the events. Cumulative runoff for PG was significantly smaller than either C or P treatments, with a reduction of 28%, compared to C. Although the mean cumulative runoff from the P treatment was 15% lower than C, the difference was not statistically significant. A graph of cumulative runoff with cumulative precipitation (fig. 4) shows C having the highest runoff throughout the experiment, PG having the lowest, and P between the two.

At RDF, the P and PG treatments generally resulted in significant reductions in runoff compared to C in rainfall events of less than 55 mm. The five events in which the P and PG treatments did not significantly reduce runoff included the two largest events of the study (30 May and 23 July 1998), and another large event on 16 November 1998. The lack of statistical differences between treatments for the 8 August 1998 event was likely due to reduced infiltration capacity caused by high antecedent moisture from 71 mm of rainfall in the four preceding days. Possible lack of significant P or PG effect on runoff in the 27 August 1998 event may have been due to greater variance due to missing data, resulting in a greater LSD value.

Prior to the first runoff event at Cotner on 19 July 1997, three storm events resulted in 18 mm of rainfall by 9 July 1997. Although no runoff was generated by these events, these first storm events affected the soil surface condition. By 9 July 1997, breakdown in soil aggregates and surface sealing was visually observed in the C plots, but the P and PG plots appeared well aggregated with very minimal sealing noted. The breakdown in aggregation and formation of a seal in C, following only 18 mm of rainfall, indicated that this soil was highly susceptible to sealing, and that the P and PG treatments were effective in increasing aggregate stability and reducing sealing. At the Cotner site, after only 29 mm of cumulative rainfall, the initially well–aggregated soil in the C plots was reduced to a smooth sealed surface. Observations of the P and PG treatments indicated that as late as 28 July 1997, after 86 mm of cumulative rainfall, the P and PG plots retained some roughness and aggregation from the original tillage.

The first rainfall event at the RDF site on 30 May 1998 was a high–intensity event, with total rainfall of 63 mm. In this storm, the lack of differences in runoff between treatments was attributed to the magnitude of the event. Visual inspection of the surface soil following this event showed that the surfaces of the C plots were smooth and that a surface seal had formed. Although there was some decline in the soil aggregation visible in the P and PG plots, the extent of surface sealing appeared to be greatly reduced compared to the C plots. The surfaces of the P and PG plots appeared rougher, compared to C. By 9 June 1998, after 78 mm of cumulative rainfall, the surfaces of the C plots appeared to be completely smooth. As late as 23 July 1998, with cumulative rainfall of 413 mm, portions of the P and PG plots appeared to retain some aggregation and roughness.

At the Cotner and RDF sites, the greater aggregation and reduced surface sealing in the P and PG treatments compared to C was most prominent after the first rainfalls. With increasing cumulative rainfall on the C plots, the level of aggregation declined quickly and the soil surfaces rapidly became smooth. Decline of soil aggregation and smoothing of the soil surface gradually developed in the P and PG treatments, but over much greater time and cumulative rainfall.

The improved aggregation, reduced surface sealing, and increased roughness of the soil surface noted in this study has been documented previously in similar studies of PAM and gypsum soil amendments (Agassi and Ben–Hur, 1992; Fox and Bryan, 1992; Stern et al. 1991). Runoff reductions realized in this study correspond with previous studies in which runoff was reduced in response to treatment with PAM and gypsum (Fox and Bryan, 1992; Levy et al., 1991; Stern et al., 1991).

Our observations of aggregation and surface seal development suggest that the reduction in runoff volume in the P and PG treatments was due to stabilization of aggregates and resistance to development of surface sealing in soils that were susceptible to seal formation. Improved aggregation and reduced surface sealing resulted in increased infiltration rates and corresponding reductions in runoff. Gypsum was applied concurrently with PAM to reduce chemical dispersion of soil aggregates, improve adsorption of PAM by clay particles, and improve flocculation. The initial surface condition of the plots was preserved by the P and PG treatments, leaving the surface rough and with a low bulk density. These conditions reduced runoff generation by allowing greater infiltration rates, more detentional storage, and decreased runoff velocity.

Erosion and Sediment Yield

At the Cotner site, the P treatment resulted in statistically significant reductions in sediment yield compared to C in eight of the nine storm events (table 2). Sediment yield reduction for these events ranged from 44% to 100% compared to C. The PG treatment resulted in significant reductions in sediment yield compared to C in seven of the storm events, with sediment yield reductions ranging from 26% to 100% compared to C. Sediment yields for the P and PG treatments were not significantly different from one another in any of the events. The cumulative sediment yield for the study period indicated significant reductions of 54% and 45%, respectively, for the P and PG treatments, compared to C. The cumulative sediment yields from the P and PG treatments were not significantly different from one another. A graph of cumulative sediment yield as a function of cumulative rainfall (fig. 3) shows that sediment losses continued to increase throughout the entire study period, most likely due to poor grass establishment for all treatments. The trends seen in this figure are very similar to those seen in the rainfall simulator study (Part I, figs. 3 and 4).

At Cotner, both the P and PG treatments were effective in significantly reducing soil loss compared to C during the three largest rainfall events (22 July, 13 August, and 17 August 1997). P and PG significantly reduced sediment yield by 26% to 62% from C, even though these events also produced the greatest runoff for all treatments. The only event in which either the P or PG treatments did not significantly reduce sediment yield was the last event of the study period (11 September 1997), although treatment means were consistent with P and PG treatment reductions in soil loss. As described previously for runoff in this event, lack of statistical differences may be a consequence of missing data and the high variance. The PAM also could have been losing some of its effectiveness by the time of the 11 September 1997 event.

At the RDF site, P significantly reduced sediment yield compared to C by 39% to 100% in nine of the storm events (table 3). PG significantly reduced sediment yield by 44% to 100% in 14 of the storm events. Sediment yields for the P and PG treatments were significantly different from each other in only two of the events. Cumulative sediment yield for the study period was reduced by 40% and 53% of C, respectively, for the P and PG treatments. The cumulative sediment yields from the P and PG treatments were not significantly different from one another. In a graph of cumulative sediment yield versus cumulative rainfall (fig. 5), sediment loss leveled off for all treatments after about 400 mm of rainfall. This was likely due to soil consolidation and vegetation establishment there.

At RDF, six of the eight events in which the P treatment did not result in a significant reduction in soil loss compared to the C were events in which soil loss was negligible across all treatments. The other two events were the storms of 6 July

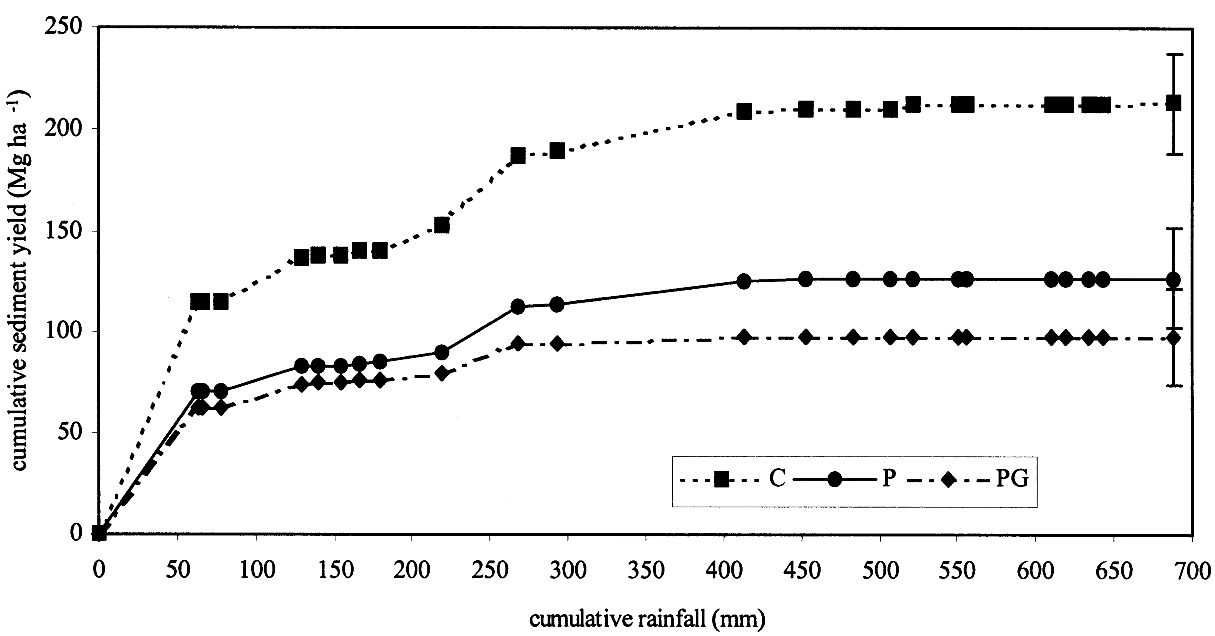

Figure 5. Cumulative sediment yield versus cumulative rainfall for the natural rainfall study at the RDF site. Bars for final points indicate P < 0.05 confidence intervals.

and 23 July 1998. These storms were very large rainfall events (depths of 49 and 120 mm), resulting in corresponding runoff depths of 21 and 93 mm in the P treatment. All events in which the PG treatment soil loss was not different from C had negligible soil loss in all treatments. PG was more effective than P in reducing soil loss in the very large rainfall events, even though the runoff conditions were similar. The P treatment was not effective in the events of 6 July and 23 July 1998, but PG resulted in soil loss reductions of 58% and 85% in these events. The only events in which P or PG were not effective in reducing sediment yield compared to C were 13 May and 27 August 1998. In both these events, sediment yield from the P and PG treatments was very low, and lack of significant differences may have been influenced by high antecedent moisture due to preceding events. In all events following 23 July 1998, the rates of soil loss were negligible across all treatments, probably due to the combined effects of soil consolidation and the establishment of grass cover at this time.

A notable difference between treatments in this study was the extent of rilling. At the Cotner site, rills were well developed in the C plots following the 22 July 1997 event. A well–developed network of rills was observed, with several rills covering the width of the plot and extending from the plot bottom to about 66% to 75% of the plot length upslope. In the P and PG plots, rilling was either not existent or minor. In the P and PG plots where rilling had started, there were only one or two rills across the plots, and rills generally extended no further than 20% of the plot length upslope. With increasing cumulative rainfall, the extent of rilling increased in all treatments, but P and PG treatments were more resistant to rill formation and growth than C. The first rainfall event at the RDF site caused an immediate effect on surface rilling across all treatments. The pattern of rill development was similar to that noted at the Cotner site. Well–developed rill networks extended across the C plot widths and extended almost the entire C plot length. Rill frequency across the P and PG plot widths was small, and rills did not extend as far in the upslope direction. Figure 6, a photo of RDF plots taken on 19 June 1998, provides a good representation of rill development across treatments. Similar reduction in rilling density in response to PAM and gypsum soil amendments has been documented in previous studies (Agassi and Ben–Hur, 1992; Fox and Bryan, 1992; Zhang and Miller, 1996).

Soil erodibility is a measure of the susceptibility of a soil to erosion, a property inherent to a soil and evaluated independently of other factors such as land slope, rainstorm characteristics, cover, and management practices (Wischmeier and Smith, 1978). Some previous studies have suggested that decreases in soil erosion in PAM and gypsum amended soils were not a result of reduced erodibility but rather a result of increased infiltration leading to reduced shear stress and transport capacity of the runoff (Levy et al., 1991; Zhang and Miller, 1996; Zhang et al., 1998). Although it was expected that reduced runoff would reduce soil loss, there were some notable events in which soil loss was significantly reduced in P and PG treatments compared to C, even though runoff was similar across all treatments. In the 22 July 1997 event at the Cotner site, soil loss in both the P and PG treatments was reduced by 62% compared to C, but runoff depths were not statistically different. In the first storm event at the RDF site, runoff was not different across treatments, but P and PG treatments reduced sediment yield by 39% and 46%, respectively, compared to C. Although runoff rates may have varied between treatments, resulting in differences in time distribution of runoff during these events, these results indicate that reduction in runoff volume is not solely responsible for the reduced sediment yield in the P and PG plots. This supposition is supported by Flanagan et al. (1997), who found that sediment delivery was reduced in PAM–

Figure 6. Photograph of three representative plots at the RDF natural rainfall site with treatments (left to right) of PAM and gypsum (PG), control (C), and PAM (P). This picture was taken on 19 June 1998, three weeks after seeding. Intense storms produced 130 mm of rainfall during this three–week period. Notice the reduced rilling and improved grass growth on the treated plots.

amended plots compared to the control under the same runoff conditions.

Studies have shown that an increase in rill frequency or density over the soil surface resulted in increased soil erosion (Meyer et al., 1975; Meyer and Harmon, 1989). The reduced amount of rilling in the P and PG plots may explain the lesser soil loss than in the more densely rilled control plots. In the C plots, the surface soil progressively sealed, and rills were initiated. Sediment yield increased as the rills incised, advanced upslope, and formed dense networks. The P and PG treatments were more resistant to rill development under similar erosive conditions, likely due to strengthened aggregates at the soil surface.

Vegetation Establishment

Vegetation establishment at the Cotner site was documented from July 1997 to November 1997, and an additional observation was made following the winter season in May 1998 (table 4). Rating values for both the P and PG were better than C for all rating dates and overall. PG vegetation establishment was ranked better than P in 16 of the 17 observations.

Observations of vegetation establishment at RDF were made from June 1998 to September 1998 (table 5). For all six observation dates, the vegetation rating of the P and PG treatments were better than C. The vegetation rating of the PG plots was better than the P treatment for 5 of the 6 observations. The overall rating of vegetation showed that P and PG improved vegetation establishment over C, and PG had better establishment than P.

Table 4. Cotner site: Vegetation establishment ratings (1 = best, 9 = worst).

Observation Date	Treatment		
	C	P	PG
19 July 1997	7.3	4.0	3.7
24 July 1997	8.0	4.0	3.0
28 July 1997	8.0	5.0	2.0
5 Aug 1997	7.7	4.7	2.7
13 Aug 1997	8.0	4.3	2.7
15 Aug 1997	8.0	5.0	2.0
19 Aug 1997	8.0	5.0	2.0
28 Aug 1997	8.0	5.0	2.0
11 Sept 1997	8.0	4.7	2.3
21 Sept 1997	8.0	4.7	2.3
28 Sept 1997	7.7	4.3	3.0
4 Oct 1997	7.7	4.3	3.0
14 Oct 1997	7.7	4.3	3.0
31 Oct 1997	7.7	4.0	3.3
7 Nov 1997	8.0	4.0	3.0
23 Nov 1997	8.0	3.3	3.7
18 May 1998	8.0	4.3	2.7
Overall	7.9	4.4	2.7

Table 5. RDF site: Vegetation establishment ratings (1 = best, 9 = worst).

Observation Date	Treatment		
	C	P	PG
12 June 1998	8.0	3.7	3.3
19 June 1998	8.0	3.3	3.7
12 July 1998	7.7	5.3	2.0
23 July 1998	8.0	4.0	3.0
1 Aug 1998	8.0	4.0	3.0
10 Sept 1998	7.7	4.3	3.0
Overall	7.9	4.1	3.0

At the Cotner site, while growth was improved in the P and PG plots, grass growth never became well established in any of the treatments. At the RDF site, grass was very well established in the P and PG treatments early in the observation period, while grass growth was poor in C. It should be noted that the vegetations ratings reported here (tables 4 and 5) are relative for each individual site, and the numeric values should not be compared between sites. The soil amendment effect on grass establishment at the RDF site is shown in figure 6.

At the Cotner site, grass seeds were observed in the runoff collection barrels as late as 22 July 1997, indicating the vulnerability of surface broadcast seeds to transport by runoff. At the RDF site, observations of plot surfaces on 4 June 1998 showed that, while considerable grass seed and fertilizer were visible in the P and PG treatments, there was no fertilizer and negligible seeds in C. The rougher surface of the P and PG treatments retained more seed and fertilizer than C did during the first storm events before seeds were germinated and established, thus more grass seeds were available for germination and growth.

An interesting feature noted in this study was the increased moisture in the P and PG treatments compared to C following rainfall events. The moisture differences were related to visually observed differences in the color of surface soil. The moisture distribution in the C plots was scattered but was more uniform in the P and PG treatments. With progressive drying, it was noted that the C plots became lighter in color, while the P and PG plots remained more moist (darker) for periods ranging from hours to days. This effect was noted at the Cotner site on the last field visit of the study year on 7 November 1997, over five months after the treatments were applied. A similar moisture retention, distribution, and persistent effect was observed at the RDF site. In studies of PAM and gypsum amendment effect on soil moisture distribution, Stern et al. (1992) found that increased infiltration in amended plots resulted in greater water content in the soil and more homogenous spatial distribution of moisture. They stated that more homogeneity in moisture distribution may contribute to improved water use efficiency by plants.

Our observations of vegetation growth and seal development in the P and PG treatments suggest the germination and establishment of seeds that were retained on the plots were improved due to the improved soil structure and reduced surface sealing. The initial seedbed was preserved, resulting in less impedance for emerging seedlings, and an improved moisture regime resulted from the increased infiltration. The improvements in vegetation establishment in this study correspond to results from other studies that have found improved plant growth with the addition of PAM amendments (Cook and Nelson, 1986; Rubio et al., 1989).

Summary

This study evaluated the effects of PAM and gypsum soil amendment treatments on runoff, sediment yield, and vegetation establishment in field plot experiments on disturbed soils. Natural rainfall plots were established on steep slopes at two locations in north central Indiana and treated with PAM (P) or PAM and gypsum (PG). The plots were meant to simulate newly constructed embankments, so they were also seeded with a typical grass mixture. Runoff and sediment resulting from natural rainfall events were measured, as well as the progress of vegetation establishment over the course of the growing season. The PAM treatments, either with or without gypsum, significantly reduced cumulative runoff and soil loss. Vegetation establishment ratings at both sites were improved by P and PG treatments. P and PG were more frequently effective in reducing soil loss than in reducing runoff, indicating that the treatments reduced soil erodibility. The PAM and gypsum amendments improved seedling germination and establishment, resulting in better grass growth compared to the control. The P and PG treatments remained persistent in reducing runoff, reducing sediment yield, and improving vegetation establishment for periods of several months at both sites.

At the Cotner site, the increased Ca^{++} concentration with concurrent application of gypsum with PAM did not yield any additional benefit over PAM applied alone for these slopes. This may have been due to calcium that was present in the new surface soil material that was created from subsoil layers including underlying glacial till. The soil survey for Cass County, Indiana, indicates that the glacial till there is calcareous (USDA, 1981), and the lower B and C soil horizons for the original soil at the Cotner site can be neutral to moderately alkaline and strongly effervescent. Compared to RDF, the soil at the Cotner site had relatively high cation exchange capacity, higher calcium ion concentration, and a more alkaline pH (table 1). Shainberg et al. (1981) found that release of calcium ions in calcareous soils could result in high enough electrolyte concentrations to prevent clay dispersion. It is very likely that at the Cotner site the critical flocculation concentration was satisfied by naturally occurring electrolytes. Thus, the electrolyte addition through gypsum amendment did not lead to any additional benefit in controlling clay dispersion.

However, at the RDF site, concurrent application of gypsum with PAM resulted in significant improvements over PAM applied alone. Interestingly, the surface–applied gypsum disappeared from the plot surface following the first storm of the study period, yet the PG treatment reduced runoff and soil loss over the long–term at this site. Future studies could examine the persistent effect of one–time gypsum application on Ca^{++} concentration at a plot surface.

These natural rainfall experiments show that the use of polyacrylamide can be a successful treatment for controlling runoff and soil loss on newly established embankments. Further research is needed to refine the appropriate rates of PAM application for a variety of slope, soil, and climatic conditions.

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