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Impact of polyacrylamide delivery method with lime or gypsum for soil and nutrient stabilization

B.J. Lepore, A.M. Thompson, and A. Petersen

Abstract: Applying lime or gypsum as soil conditioners in concert with polyacrylamide (PAM) can reduce soil erosion more than applying the conditioner or the PAM alone, but little is known about the relative impact of different combined application methods. Laboratory rainfall simulations were conducted for 1 hour with runoff collected in 20-minute intervals to compare runoff sediment, sediment-bound P and NH_4-N, and dissolved Ca and S loads. Treatments were bare soil, lime, gypsum, PAM-coated lime or gypsum prills, and lime or gypsum prills applied with separate PAM-coated paper mulch granules. All treatments, except gypsum, reduced sediment and sediment-bound P loads compared to bare soil ($p < 0.01$), and all PAM-conditioner treatments were more effective than the respective conditioner alone. Load reductions compared to bare soil were greatest for PAM-coated lime and PAM-coated gypsum, with sediment reductions of 83% and 69%, respectively ($p < 0.01$). Sediment P loads followed trends in sediment loads, while sediment NH_4-N load reductions were, in general, slightly smaller and statistically less significant. Sediment load reductions were 16% greater for PAM-coated lime than lime applied with separate PAM granules and were 11% greater for the PAM-coated gypsum than gypsum applied with separate PAM granules. However, these differences were not statistically significant ($p > 0.05$). Runoff dissolved Ca loads (for lime and gypsum) and S loads (for gypsum) were significantly reduced by the PAM-coated conditioner treatments compared to the conditioner applied with separate PAM granules. Dissolution tests indicated that the PAM coating reduces the dissolution rate of the lime and gypsum, suggesting a possible mechanism accounting for differences between the two PAM treatments. This work suggests that the use of PAM in conjunction with lime or gypsum can be an effective erosion control tool, reducing sediment and nutrient losses and that coating lime or gypsum with PAM may have added benefit.

Key words: erosion control—gypsum—lime—polyacrylamide—soil conservation—rain-fed agriculture

The nonpoint source pollution of surface and groundwater resources continues to be of significant concern for both its ecological and economic impacts (USEPA 2003; USEPA 2007). The transport of sediment, fertilizers, and other nutrients from agricultural fields to receiving waters through erosion and runoff is one of the largest components of nonpoint source pollution (USEPA 2003).

Lime ($CaCO_3$) and Gypsum ($CaSO_4 \cdot 2H_2O$) are two of the most commonly applied soil conditioners in modern agriculture. Lime, primarily applied to increase soil pH (Kelling and Schulte 2004) is most commonly added to soil through crushed dolomite and limestone. In 2001, an estimated 16.1 Tg (1.77×10^7 tn) of limestone and 4.0 Tg (4.4×10^6 tn) of dolomite were applied in the United States (USEPA 2004). Gypsum is traditionally used as a soil conditioner to improve soil aggregation, stability, and surface infiltration. Nearly 1.8 Tg (2.0×10^6 tn) of gypsum were applied to US agricultural land in 2006 (USGS 2006).

Although surface application of lime has primarily been used to overcome soil acidity, results from several studies suggest it can also be used to enhance soil structural stability (Roth and Pavan 1991; Baldock et al. 1994; Chan and Heenan 1998; Chan and Heenan 1999), thereby enhancing infiltration and reducing runoff and sediment loss. The application of gypsum ($CaSO_4 \cdot 2H_2O$) or gypsiferous materials (GM) (e.g., phosphogypsum, coal combustion by-products, etc.) have been shown to increase infiltration rates and decrease runoff and sediment losses (Kazman et al. 1983; Keren et al. 1983; Smith et al. 1990; Zhang et al. 1998; Tang et al. 2006). Both lime and gypsum increase soil solution electrolyte concentration, replacing exchangeable Na with Ca, and decreasing the tendency of soil clay to disperse and form a surface seal (Keren et al. 1983). Thus, soil amendments containing lime and gypsum have been and will continue to be used in agriculture to minimize the dispersion of clay particles and reduce soil surface sealing, which decreases infiltration rates and increases runoff volumes and sediment loss.

Water soluble linear anionic polyacrylamides (PAM) are also used to enhance aggregate stability, promote infiltration, and reduce runoff and erosion. Sojka et al. (2007) conducted a thorough review of the literature regarding PAM use in land management. The practice of PAM application has been widely accepted in irrigated agriculture, where small concentrations (<10 mg L^{-1} [ppm]) and very low application rates (< 0.7 kg ha^{-1} [0.8 lb ac^{-1}]) in advancing water in furrows effectively increases infiltration and decreases sediment loss (Lentz et al. 1992; Lentz and Sojka 1994). Sprinkler irrigation is also amenable to PAM application and has been shown to effectively reduce runoff and erosion at low concentrations (10 to 20 mg L^{-1}) and application rates (2 to 4 kg ha^{-1} [2.2 to 4.5 lb ac^{-1}]) (Aase et al. 1998; Bjorneberg et al. 2003). Low PAM application rates have been effective in irrigated agriculture because PAM can be applied directly with irrigation water. However, surface application of PAM in rain-fed agriculture has required larger application rates (>20 kg ha^{-1} [22 lb ac^{-1}]) to effectively increase infiltration and reduce erosion (Smith et al. 1990; Ben-Hur and Keren 1997). These high application rates have made PAM use impractical

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and economically challenging for producers in rain-fed areas due to the amount of water and labor required for effective application. Recently though, Petersen et al. (2007) showed that surface application of a new PAM emulsion formulation was effective at 5.0 kg PAM ha^{-1} (5.6 lb PAM ac^{-1}) in reducing sediment loss in rain-fed agricultural fields, suggesting that this PAM formulation has the potential to become an economical erosion control practice.

When applied alone, lime, gypsum, and PAM are effective soil conditioners. However, the combined application of PAM with lime and gypsum to soil can be advantageous in that the provision of divalent cations in the form of Ca^{2+} enhances cation bridging and the sorption of PAM to soil particles (Laird 1997; Green et al. 2000; Nishimura et al. 2005; Sojka et al. 2007). Several studies have shown the combination of gypsiferous materials (GM) and PAM to improve infiltration and related properties and reduce erosion relative to applying either alone (Levin et al. 1991; Agassi and Ben-Hur 1992; Flanagan et al. 1997; Sellers and Hickman 2001; Yu et al. 2003; Cochrane et al. 2005; Tang et al. 2006). Yu et al. (2003) reported mixed results, concluding that dry PAM granules applied with gypsum were very effective in increasing infiltration and reducing runoff but were not effective in controlling soil erosion.

Investigations into different methods of delivering PAM in combination with lime or gypsum are limited. For controlling erosion, Peterson et al. (2002) found that sprayed PAM applied with gypsum was more effective than dry PAM granules with gypsum in controlling erosion. Important considerations when determining the method of combined PAM-GM or PAM-lime application are ease of application, degree of modification from current methods, cost, and efficacy. Lime and gypsum are commonly applied in pelletized form (prills) for ease of spreading by traditional mechanical spreaders. Two likely methods of applying PAM in conjunction with GM or lime prills will be to (1) coat the prills themselves with PAM or (2) apply a PAM carrier granule in conjunction with GM or lime prills. The new PAM formulation used by Petersen et al. (2007), with slight modifications, is now being utilized in commercial products as both a PAM-coated gypsum and lime prill (e.g., Fast Acting Lime and Fast Acting Gypsum [ENCAP, LLC; Green Bay, WI]), and as a PAM carrying dry paper mulch granule (e.g., PAM-12 [ENCAP, LLC]). One of the critical factors determining the usefulness of any soil amendment for large-scale agricultural application is the cost per area treated. Although pricing structures are yet to be determined for PAM applications to rain-fed agricultural fields, the method of PAM-lime or PAM-gypsum delivery is likely to have a significant impact on the cost, making it important to better understand the relative effectiveness of different PAM-lime or PAM-gypsum delivery methods. The objective of this study was to determine the effectiveness of applying PAM-coated prills of gypsum or lime at reducing soil erosion and nutrient loss compared to applying gypsum or lime prills with a separate PAM carrying granule.

Methods and Materials

Soil Conditioner/Polymer Products. All polymer products used in this study are commercially available. Liquid TRIPAM and TRIPAM FS (Soil Net LLC, Madison, Wisconsin) are proprietary mixtures of different molecular weight anionic linear PAM (25% 5 to 8 Mg [11,000 to 18,000 lb] mol^{-1}, 25% 12 to 17 Mg [26,000 to 37,000 lb] mol^{-1} and 50% 28 to 35 Mg [62,000 to 77,000 lb] mol^{-1}) in liquid and fine powder forms, respectively, designed for delivery to soil by a solid carrier (e.g. paper mulch granules, lime or gypsum prills). All PAM molecules have a 35 mol% charge density. The solid carrier delivery method for PAM was developed and is patented by ENCAP, LLC. Liquid TRIPAM is a PAM emulsion with solid particles in suspension ranging from 10^{-2} to 2 µm (3×10^{-7} to 8×10^{-5} in). By covering the surface of the treated granules, the small sized particles in emulsion lead to increased polymer activity and efficiency. The TRIPAM fine powder (FS) consists of polymer particles in the size range of 0.2 to 50 µm (8×10^{-6} to 2×10^{-3} in). The powder is coated onto granules after treatment with Liquid TRIPAM to increase polymer contact with soil.

Liquid and fine powder TRIPAM were delivered to the soil in two ways: (1) as a coating of lime and gypsum prills (supplied by SoilNet LLC, Madison, Wisconsin) or (2) through PAM-12, a paper mulch granule (supplied by ENCAP LLC, Green Bay, Wisconsin). PAM-12 uses ENCAP's Advanced Soil Technology, which impregnates a paper mulch granule with Liquid TRIPAM and coats the granule with TRIPAM FS. In the case of the coated lime product, an additional 1 g (2×10^{-3} lb) of superactive $Ca(OH)_2$ is added to 100 g (2×10^{-1} lb) of the lime product to supply a readily available source of Ca^{2+}.

Table 1
Properties of Plano Silt Loam used in simulated rainfall experiments.

Sand content (%)	21
Silt content (%)	60
Clay content (%)	19
pH	7.4
Organic matter (%)	4.0
Bray P (ppm)	32
Total P (ppm)*	613
K (ppm)	120
Ca (ppm)	2,277
Mg (ppm)	769
Exchangeable Na (ppm)	17
Soluble salts (mhos × 10^{-5} cm^{-1})	3,740

* Estimated using organic matter percent and Bray-P (WPI 2008).

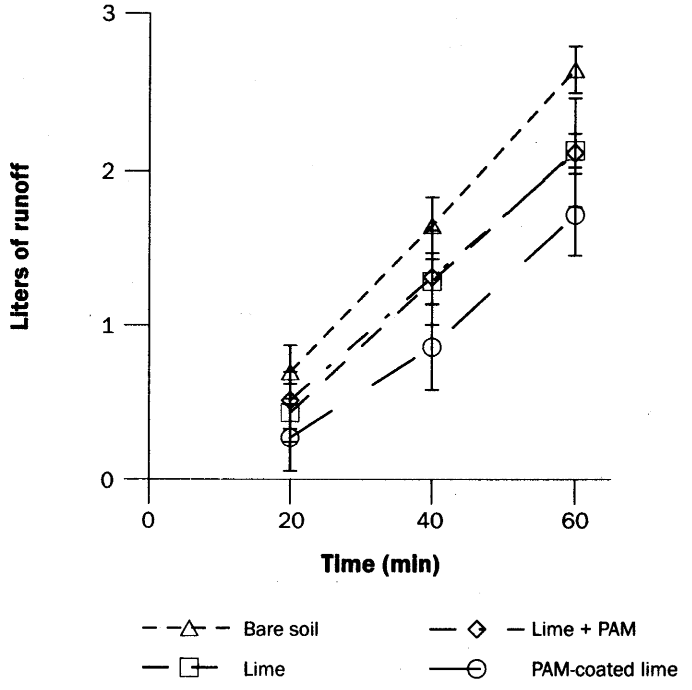
Rainfall Simulations. Infiltration, runoff, erosion, and nutrient transport were studied using the same laboratory rainfall simulator used in previous PAM tests by Petersen (2006). The drip-type simulator consisted of an enclosed polyvinyl chloride (PVC) chamber with approximately 700 hypodermic needles protruding from the base of the chamber in a 25 × 25 mm (1 × 1 in) grid spacing. Water was pumped from a holding tank through a 19 mm (0.75 in) hose using a 1.1×10^{-3} MW (1.5 hp) submersible pump. A pressure regulator maintained a constant water pressure (~7 kPa [1 PSI]) in the enclosed chamber, and a ball valve allowed flow to the simulator to be turned on or off. The enclosed chamber was positioned 1.5 m (5 ft) above a sloped platform (10%) on four support legs. Small oscillating fans positioned on the support columns of the simulator induced spatially random drop distributions on the test area below the simulator. Average droplet diameter was 3.5 mm (1.4×10^{-1} in), determined volumetrically by collecting 50 drops from twenty randomly selected needles. The 1.5 m (5 ft) drop height produced drops with a fall velocity of 4.94 m s^{-1} (16.2 ft sec^{-1}) according to Epema and Riezebos (1983).

Plano silt loam soil obtained from agricultural fields at Arlington Agricultural Research Station (Arlington, Wisconsin) was used in all experiments (table 1). Soil was taken from the upper 10 cm (4 in) of the soil surface, air-dried, crushed, and passed through a

4.0 mm (0.2 in) sieve to maintain soil uniformity throughout the tests. The soil was spread evenly to a depth of 2.5 cm (1.0 in.) in two lifts over a 5.1 cm (2.0 in) pea gravel base layer in soil boxes measuring 0.457 long × 0.203 wide × 0.089 m deep (18.0 × 8.00 × 3.50 in). Deionized water was applied to each soil lift using a hand sprayer to achieve an overall moisture content of 20% by volume. The soil was compacted to a bulk density of 1.2 g cm^{-3} (4.3 × 10^{-2} lb in^{3}) by pressing the soil with a flat piece of PVC to a known depth. Treatments were then spread by hand on the soil surface, and the boxes were covered and allowed to rest for 24 hours before rainfall simulations were performed.

Figure 1

Cumulative liters of runoff and standard deviation generated by 60 minutes of 65 mm h^{-1} simulated rainfall for lime experiments.



Three lime and three gypsum treatments, totaling six treatments, were tested in addition to a bare soil control. The three treatments were (1) soil conditioner, where the conditioner (lime or gypsum) was applied to the soil surface at an application rate of 280 kg ha^{-1} (250 lb ac^{-1}); (2) conditioner + PAM, where dry PAM-12 granules provided by ENCAP LLC (Green Bay, Wisconsin) were applied to the soil surface at 224 kg ha^{-1} (200 lb ac^{-1}) (PAM application rate of 5.6 kg ha^{-1} [5.0 lb ac^{-1}]) in addition to the conditioner (lime or gypsum) at 280 kg ha^{-1}; and (3) PAM-coated conditioner, where the PAM-coated conditioner was applied to the soil surface at 280 kg ha^{-1} (250 lb ac^{-1}) (PAM application rate of 5.6 kg ha^{-1} [5.0 lb ac^{-1}]). The PAM application rates for all treatments (lime, gypsum, and paper mulch) consisted of an approximate Liquid TRIPAM to TRIPAM FS ratio of 2.75:1. All treatments were replicated four times.

Three soil boxes were positioned side-by-side on the sloped platform to allow simultaneous testing of three treatments. All treatments, including individual replicates, were randomized with respect to soil box position under the rainfall simulator and experimental order. Lime and gypsum treatments were randomized separately. This randomization resulted in three of the bare soil replicates being run with the lime treatments and the fourth bare soil replicate run with the gypsum treatments. All simulations were completed in three days, and any blocking effect introduced by randomizing the lime treatments separately from the gypsum treatments was minimized by recalibrating the rainfall simulator at the beginning and end of each day. Rainfall was simulated at approximately 6.5 cm h^{-1} (2.5 in hr^{-1}) for 60 minutes. Each soil box had a fixed gutter along the downslope edge with a PVC pipe outlet from which runoff was collected. An infiltration outlet was positioned at the underside of each soil box, which allowed infiltrated precipitation to leach from the soil. Runoff was collected continuously over three time intervals: 0 to 20, 20 to 40, and 40 to 60 minutes after starting the rainfall simulation. Each sample was weighed, and a subsample of approximately 60 mL (2.0 oz) was filtered with a 0.45 µm (1.8 × 10^{-5} in) pore size filter and analyzed by the Soil and Plant Analysis Laboratory at the University of Wisconsin-Madison for dissolved calcium (Ca) for both lime and gypsum treat-

Table 2

Lime experiment total runoff sediment and sediment bound P and NH_4-N (kg ha^{-1}) and standard deviations for 0 to 60 minutes of simulated rainfall.

	Runoff sediment (all units are kg ha^{-1})											
	Sediment				**P**				**NH_4-N**			
Bare soil	6,843	±	1,192	a	4.7	±	0.8	a	0.3	±	0.1	a
Lime	4,761	±	1,184	b	3.3	±	0.7	b	0.2	±	0.1	ab
Lime + PAM	2,237	±	263	c	1.6	±	0.2	c	0.1	±	0.04	b
PAM-coated lime	1,189	±	337	c	0.8	±	0.3	c	0.1	±	0.04	b

Note: Means followed by the same letter are not significantly different ($p < 0.05$)

Figure 2
(a) Cumulative sediment load during 60 minutes of simulated rainfall (total precipitation ~ 65 mm) for bare soil and lime treatments. (b) Percent reduction in cumulative sediment load compared to bare soil.

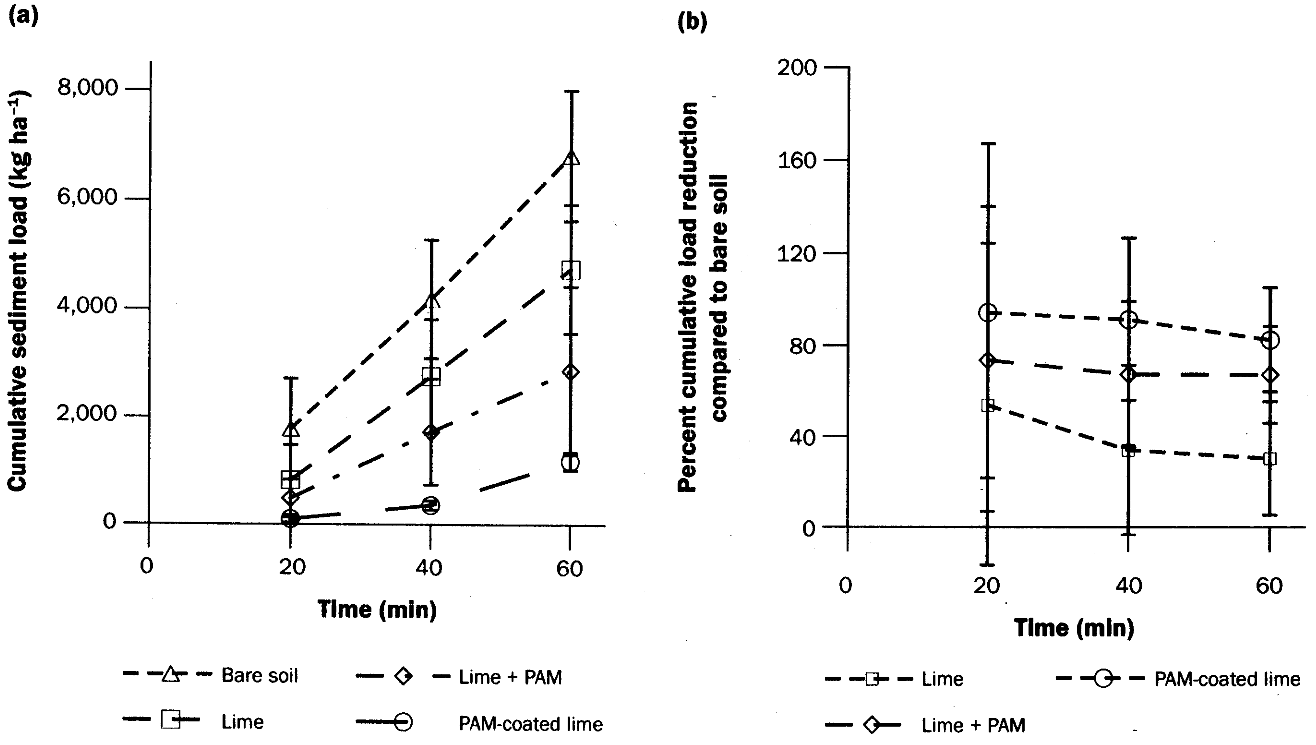


Table 3
Lime experiment percent reduction in 60 minute cumulative sediment load and sediment bound P and NH_4-N loads. Comparisons are made between all three experimental treatments and bare soil as well as between two PAM treatments and lime. Adjusted *p*-values are in parentheses.

	Runoff sediment		
	Sediment	P	NH_4-N
Percent reduction compared to bare soil			
Lime	30 (0.03)	31 (0.02)	37 (0.18)
Lime + PAM	67 (<0.01)	65 (<0.01)	75 (<0.01)
PAM-coated lime	83 (<0.01)	82 (<0.01)	74 (<0.01)
Percent reduction compared to lime			
Lime + PAM	53 (0.01)	50 (0.01)	59 (0.18)
PAM-coated lime	75 (<0.01)	74 (<0.01)	59 (0.18)

ments and dissolved sulfur (S) for gypsum treatments. The remaining runoff sample was oven dried at 105°C (221°F) for at least 24 hours. Dried runoff sediment was weighed, collected, and sent to the University of Wisconsin-Madison Soil and Plant Analysis Laboratory (Madison, Wisconsin) for analysis of total phosphorus and ammonium-nitrogen (NH_4-N).

Calcium Dissolution Tests. To determine the rates of Ca dissolution from the lime and gypsum compared to their PAM-coated counterparts, 1.5 g (3.3×10^{-3} lb) of material was added to 2.0 L (0.53 gal) of deionized water and stirred with a magnetic stir bar. Starting 1 minute after adding the material, and every minute thereafter until 10 minutes, aliquots of slightly greater than 5 ml (0.2 oz) where withdrawn by a syringe from the solution and were immediately filtered through a 0.45 µm (1.8×10^{-5} in) syringe filter. The samples were analyzed for dissolved Ca concentrations using a standard flame atomic absorbtion method (USEPA 1983) and a GBC 932AB Plus spectrometer (GBC Scientific Equipment, Hampsire, Illinois). All dissolution tests were repeated three times. For the lime dissolution tests, the additional superactive $Ca(OH)_2$ described above was not added to the PAM coated lime treatment to insure that all dissolved calcium was from the lime.

Data Analysis. Sediment loads, nutrient loads, mineral loads, and runoff volumes were accumulated over the duration of the rainfall simulation for each replicate and then averaged, and the percent reduction in each variable was determined as

$$\text{Percent reduction} = \frac{A_c - A_t}{A_c}, \qquad (1)$$

where A_c and A_t are the average accumulated sediment load, nutrient load, mineral load, or runoff volume from the control and the average sediment load, nutrient load, mineral load, or runoff volume from the treatment, respectively.

Data obtained from the rainfall simulations were analyzed with SAS v. 9.1.3 (SAS Institute Inc., Cary, North Carolina) using the MIXED procedure and a Bonferroni method Post hoc test to obtain critical levels of significance ($p < 0.05$).

Results and Discussion

Lime: Runoff, Sediment, and Sediment-bound Phosphorus and Ammonium-Nitrogen. The two PAM treatments reduced cumulative runoff with respect to the control with a lime + PAM reduction of 20% ($p = 0.048$) and a PAM coated lime reduction of 35% ($p = 0.001$) (figure 1). There were no significant differences between lime and bare soil ($p = 0.058$), between lime and either PAM treatment ($p > 0.18$), or between the two PAM treatments ($p = 0.21$).

When compared with bare soil, all treatments decreased cumulative sediment loads throughout 60 minutes of simulated rainfall (figure 2a). After 60 minutes of precipitation, both PAM treatments were more effective than lime alone ($p < 0.01$), but were not significantly different from each other ($p = 0.70$) (table 2). The trend in sediment load throughout the experiment was bare soil > lime > lime + PAM > PAM-coated lime. The sediment load reduction relative to bare soil after 20 minutes was 54%, 74%, and 94% for lime, lime + PAM, and PAM-coated lime, respectively (figure 2b). After 40 minutes, the sediment load reductions had fallen to 34%, 67%, and 91%, and after 60 minutes they were 30%, 67%, and 83% (table 3). There was also a 53% and 75% cumulative sediment load reduction after 60 minutes when comparing the lime + PAM and PAM coated lime treatments, respectively, to lime treated soil (table 3). The trends and percent reductions in sediment bound P and NH_4-N loads were similar to those of sediment load, with the exception of the 60 minute cumulative NH_4-N loads, which were not significantly different for lime than bare soil or the two PAM treatments ($p = 0.18$) (tables 2 and 3). While the variability in sediment loads were relatively high, the differences in sediment load reduction compared to runoff reduction indicate that reduction of sediment loss from the soil boxes is not simply due to decreased runoff (or increased infiltration) but is also due in part to the stabilization of primary soil particles by the treatments, with the order of

Figure 3

Cumulative dissolved Ca load during 60 minutes of simulated rainfall (total precipitation ~ 65 mm) for bare soil and lime treatments.

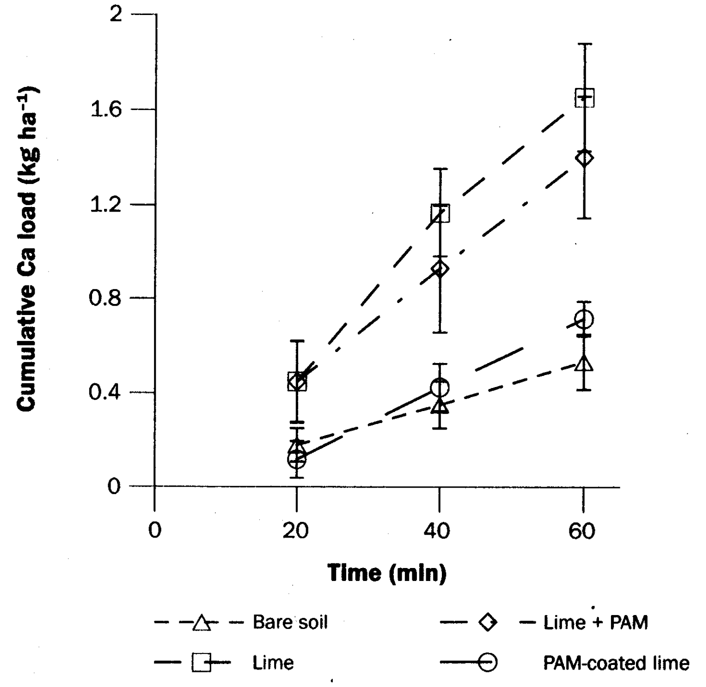


Figure 4

Ten minutes of calcium dissolution from lime and PAM-coated lime after adding 1.5 g of material into 2 L of deionized water while stirring with a magnetic stir bar.

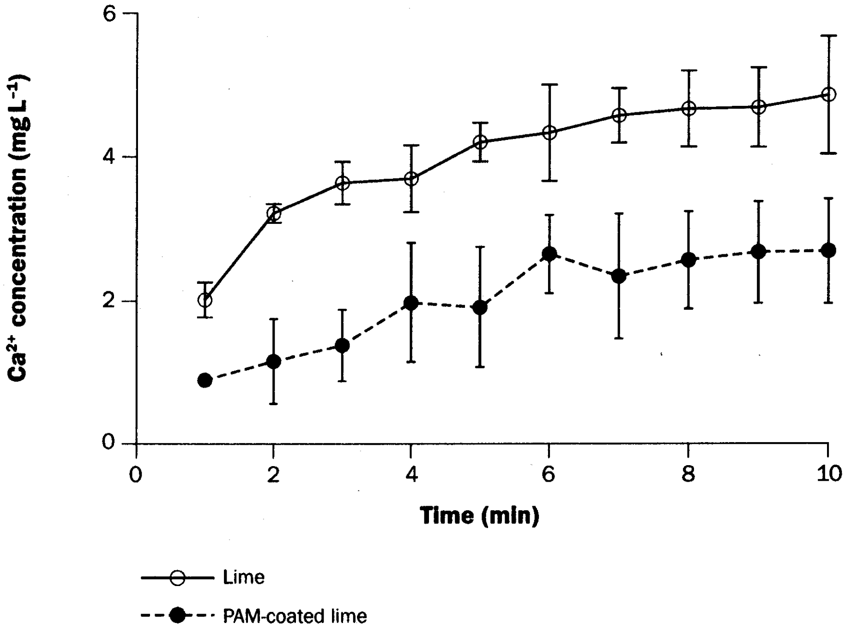
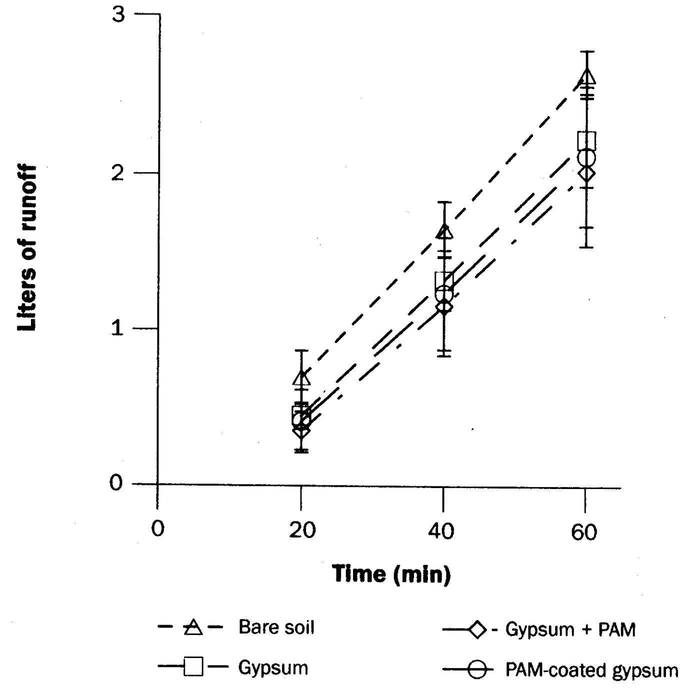


Figure 5

Cumulative liters of runoff and standard deviation generated by 60 minutes of 65 mm h^{-1} simulated rainfall for gypsum experiments.



effectiveness being PAM-coated lime > lime + PAM > lime.

Lime: Dissolved Runoff Calcium. Throughout the 60-minute rainfall simulation, cumulative Ca loads fell into two statistically significant groups: (1) bare soil and PAM-coated lime and (2) lime and lime + PAM (figure 3). We attribute such groupings to three different mechanisms, which may be working simultaneously: (1) decreased dissolution rate of lime due to PAM coating, (2) different degrees of mixing between PAM and Ca (supplied by the lime) for the two PAM treatments which impacts the efficiency of cation bridging and (3) increased infiltration and vertical Ca transport in the vicinity of PAM granules. The lime + PAM treatment consists of separate granules of PAM-12 and lime which, when applied to the soil surface, are not likely physically connected to each other. During the time required to activate the water soluble PAM, much of the lime may have already dissolved and been transported in runoff. Conversely, the PAM coating used in the PAM-coated lime treatment may slow the dissolution of Ca. The slower Ca dissolution coupled with retention of Ca through cation bridging of PAM molecules and soil particles can decrease the Ca loss in runoff.

To test whether the calcium dissolution rate is affected by coating the lime with PAM, the Ca dissolution was monitored over time (figure 4). The Ca dissolved from the lime faster than from the PAM-coated lime with the most significant differences in Ca dissolution rate occurring within the first minute of adding the material to the water. The depressed dissolution rate for PAM-coated lime indicates that encapsulation of lime by PAM is likely one factor in the complex interactions between Ca, soil, pH, and PAM, which lead to decreased soil and Ca loss from the PAM-coated lime when compared to lime and lime + PAM treatments.

Gypsum: Runoff, Sediment, Sediment-Bound Phosphorus, and Sediment-Bound Ammonium-Nitrogen. No significant differences in cumulative runoff were observed between treatments ($p > 0.9$) (figure 5). All treatments decreased cumulative sediment loads when compared to bare soil throughout 60 minutes of simulated rainfall (figure 6a). Similar to the lime treatments, both gypsum-PAM treatments were more effective than gypsum alone ($p = 0.02$) but were not significantly different from each other ($p = 1$) (table 4). However, also similar to the lime treatments, the average sediment load from the PAM-coated gypsum was continually lower than gyspum + PAM throughout the 60-minute experiment (figure 6a). When compared directly to bare soil, the sediment load reductions after 20 minutes of simulated rainfall were 54%, 73%, and 91% for gypsum, gypsum + PAM, and PAM-coated gypsum, respectively (figure 6b). After 40 minutes, the sediment load reductions were 19%, 59%, and 73%, and after 60 minutes, they were 18%, 58%, and 69% (table 5). These reductions were similar, although slightly lower, than their corresponding lime treatments. The cumulative sediment loads after 60 minutes fell into two statistically differ-

Table 4

Gypsum experiment runoff sediment and sediment-bound P and NH_4-N (kg ha^{-1}) and standard deviations for 0 to 60 minutes of simulated rainfall.

	Runoff sediment (all units are kg ha^{-1})											
	Sediment				P				NH_4-N			
Bare soil	6,843	±	1,192	a	4.7	±	0.8	a	0.3	±	0.1	a
Gypsum	5,591	±	497	a	4.0	±	0.3	a	0.2	±	0.1	a
Gypsum + PAM	2,879	±	1,561	b	2.1	±	1.0	b	0.1	±	0.01	ab
PAM-coated gypsum	2,095	±	634	b	1.5	±	0.3	b	0.1	±	0.1	b

Note: Means followed by the same letter are not significantly different by ANOVA ($p < 0.05$)

Figure 6

(a) Cumulative sediment load during 60 minutes of simulated rainfall (total precipitation ~ 65 mm) for bare soil and gypsum treatments. (b) Percent reduction in cumulative sediment load compared to bare soil.

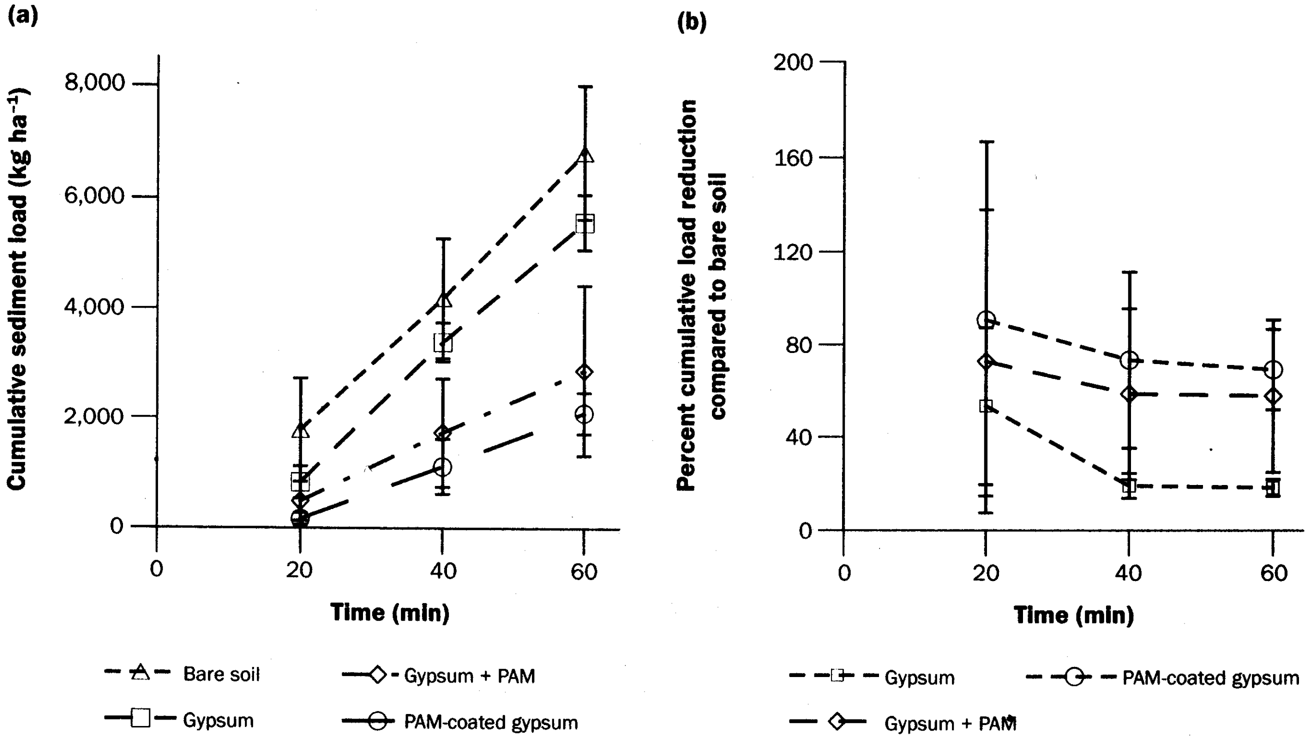


Table 5

Gypsum experiment percent reduction in 60 minute cumulative sediment load and sediment bound P and NH_4-N loads. Comparisons are made among all three experimental treatments and bare soil as well as between two PAM treatments and gypsum. Adjusted *p*-values are in parentheses.

	Runoff sediment		
	Sediment	P	NH_4-N
Percent reduction compared to bare soil			
Gypsum	18 (0.73)	16 (0.92)	28 (0.63)
Gypsum + PAM	58 (<0.01)	55 (<0.01)	28 (0.05)
PAM-coated gypsum	69 (<0.01)	69 (<0.01)	57 (0.02)
Percent reduction compared to gypsum			
Gypsum + PAM	49 (0.02)	46 (0.02)	31 (1.00)
PAM-coated gypsum	63 (<0.01)	63 (<0.01)	41 (1.00)

ent groups: (1) bare soil and gypsum and (2) gypsum + PAM and PAM-coated gypsum (table 4). The apparent separation of slopes in figure 6a into the same two groups likely reflects significant differences in how PAM with gypsum versus gypsum alone contributes to soil consolidation and stability. There was also a 49% and 63% cumulative sediment load reduction when comparing gypsum + PAM and PAM-coated gypsum treatments, respectively, to gypsum treated soil (table 5). Although both PAM treatment means were each statistically different than the gypsum treatment means ($p < 0.02$), they were not significantly different than each other ($p = 1$). However, as was the case for the lime treatments, PAM-coated gypsum resulted in greater percent sediment load reduction than gypsum + PAM. The trends for sediment bound P and NH_4-N were similar to those of sediment load with the exception that mean cumulative NH_4-N loads for gypsum + PAM were not significantly different than other treatments (table 4).

Gypsum: Dissolved Runoff Calcium and Sulfur. The dissolved Ca and S runoff loads track each other and for both the constituents fall into two statistical groups: (1) bare soil and PAM-coated gypsum, and (2) gypsum + PAM and gypsum (figure 7). As in the lime study, such grouping may be attributed to (1) different dissolution rates of PAM and gypsum, (2) different degrees of mixing between PAM and Ca (supplied by the gypsum) and the resultant increased opportunity for Ca to be used as a bridge in PAM-soil binding and (3) increased Ca and S infiltration in the vicinity of the applied PAM coated gypsum granules.

Because S is not expected to play a significant role in polymer-soil bridging, the reduction in cumulative S load for PAM-coated gypsum compared to gypsum + PAM (figure 7b) indicates that cation bridging may not be the most likely reason for the observed Ca reduction patterns (figures 3 and 7a).

Figure 7

Cumulative calcium (a) and sulfur (b) load during 60 minutes of simulated rainfall (total precipitation ~ 65 mm) for bare soil and gypsum treatments.

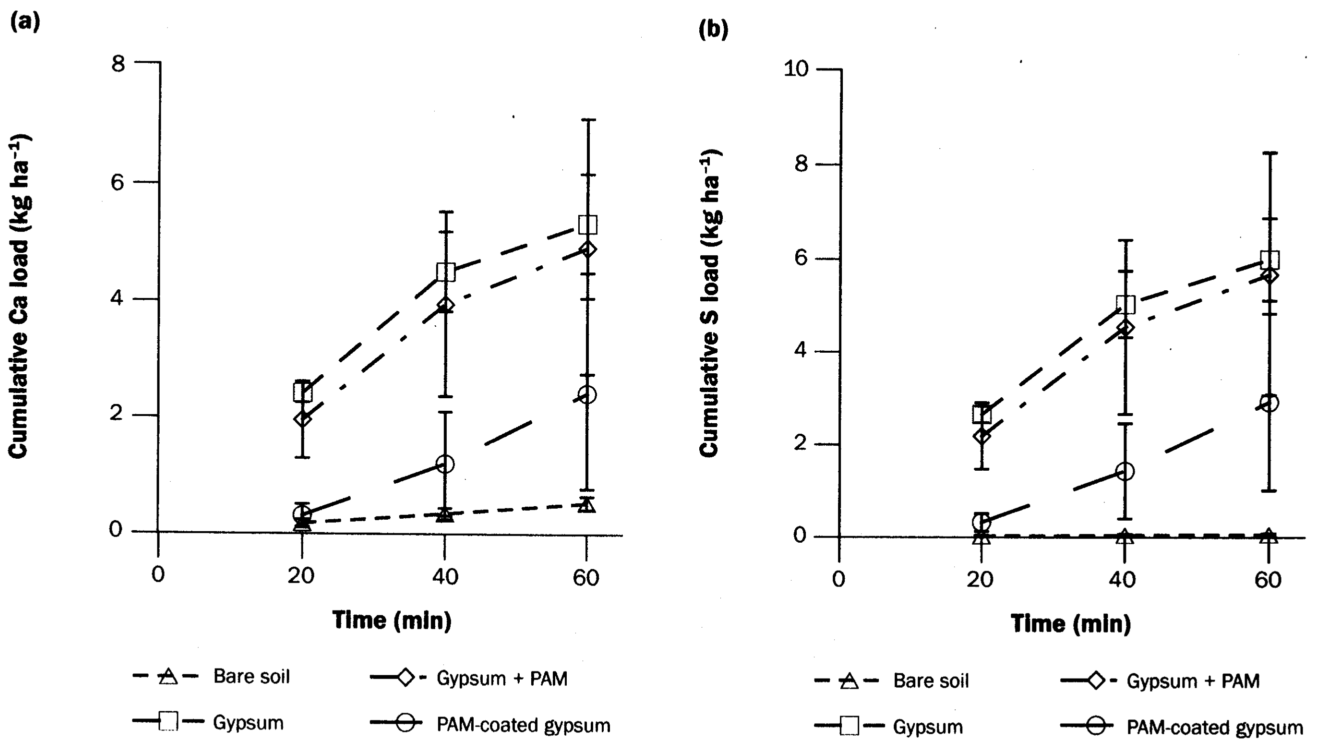
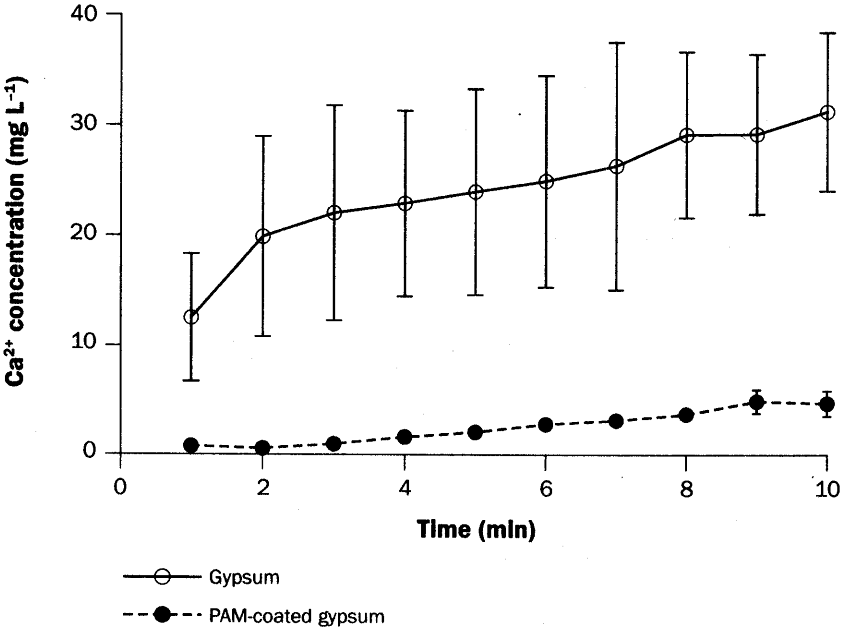


Figure 8

Calcium dissolution from gypsum and PAM-coated gypsum after adding 1.5 g of material into 1 L of deionized water while stirring with a magnetic stir bar.



Dissolution tests of the gypsum treatments identical to those described for the lime treatments were conducted to obtain information on the importance of dissolution rate. PAM-coated gypsum dissolution was much slower than uncoated gypsum from the start of the test (figure 8) with dissolved Ca differences throughout the duration of the dissolution test.

Comparisons Between Lime and Gypsum Treatments. Cumulative runoff was similar for lime and corresponding gypsum treatments (figures 1 and 5). However, cumulative sediment yields were 1.2, 1.8, and 1.3 times greater for gypsum, PAM-coated gypsum, and gypsum + PAM, respectively, than their lime counterparts, although differences were not significant at the $p < 0.05$ level. While the Ca application rate for lime treatments was 1.7 times that of gypsum treatments, runoff dissolved Ca loads were more than three times higher for gypsum treatments than their lime counterparts (figures 3 and 7a), reflecting the higher solubility of gypsum than lime. Additionally, approximately six times more Ca was in solution throughout the dissolution tests for gypsum than for lime (figures 4 and 8). The difference in dissolution rate between the coated and uncoated conditioner was much greater for gypsum than for lime, suggesting that perhaps the PAM adheres more strongly to gypsum prills.

Summary and Conclusions

Control of soil erosion in rain-fed agriculture is a critical element in preserving the productivity of farmland and the quality of surface waters. To this end, it is important that methods making erosion control practicable and economical for farmers and land owners be developed and optimized. Lime, gypsum, and PAM have all been used to improve soil aggregation, improve infiltration, and reduce erosion. New formulations of PAM are readily soluble and effective at low rates, allowing them to be more useful in rain-fed agriculture than they have in the past. Because lime and gypsum are already frequently applied as soil conditioners, using PAM to enhance their impact is desireable. The findings in this study indicate that PAM improves the erosion control impact of both lime and gypsum. Additionally, applying PAM as a coating around the lime and gypsum appears slightly more effective in controlling erosion and sediment-bound nutrient losses and in retaining the Ca and S applied with the lime and gypsum than applying the PAM in a separate granule. When delivering PAM as a coating, the physical proximity of PAM and Ca leads to greater cation bridging of PAM to soil and increased soil stability compared to separately applying PAM and Ca, as is the case when lime or gypsum is applied with a separate paper mulch PAM carrier.

Finally, lime was slightly more effective than gypsum when applied both alone and in concert with PAM. Most research comparing lime and gypsum applications to soils is focused on the long-term impacts on soil chemical and physical properties, which do not give obvious insight into the complex interactions between PAM, soil chemistry (pH, EC, SAR, etc.), and these conditioners that occurs under the intense simulated rainfall and relatively short term of these experiments. Nonetheless, these interactions are an important area for future research in order to optimize the effectiveness and minimize the cost of combined application of PAM and lime or gypsum.

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