INFLUENCE OF POLYMER CHARGE TYPE AND DENSITY ON POLYACRYLAMIDE AMELIORATED IRRIGATED FURROW EROSION

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ABSTRACT

Previous experiments have shown that an initial application of 5-10 g m^{-3} (5-10 ppm) polyacrylamide to furrow irrigation water during flow advance can substantially reduce sediment loss. This study determined polyacrylamide charge type or charge density influences on furrow erosion. The study area was located near Kimberly, Idaho; soil was Portneuf silt loam (coarse-silty, mixed, mesic, Durixerollic Calciorthid); and slope was 1.5%. Polyacrylamides with contrasting charge type (neutral, anionic, cationic) and charge density (0, 8-10, 19-20, 30-35%) were employed in the treatments. Polymers were applied at a concentration of 10 g m^{-3} (10 ppm) during the initial 30 min of each treated irrigation, and a 10 min additional application was introduced every 4 hrs (twice) during the remainder of the irrigation. Inflow rate was 23 L min^{-1} (6 gpm) during furrow advance, and 15 L min^{-1} (4 gpm) for the balance of the irrigation. The nature of charge on the polyacrylamide did influence efficacy of erosion control. On Portneuf soils, the order of effectiveness with respect to PAM charge type was: anionic > neutral > cationic. Within anionic and cationic charge types, polyacrylamide efficacy increased with increasing charge density.

INTRODUCTION

Organic polymers, mainly polyacrylamides (PAM) and polysaccharides have been used in laboratory studies to maintain the structure and permeability of soils subjected to artificial rainfall (Helalia and Letey, 1988b; Levy et al., 1991; Shainberg et al., 1990). In a field study, Mitchell (1986) increased furrow infiltration into a clayey soil by 30-57% during the first 4 hr of an irrigation by applying 150 g m^{-3} (150 ppm) PAM to the irrigation water during furrow advance. Lentz et al. (1992) demonstrated that an initial small application of anionic polyacrylamide (PAM) to irrigation water nearly eliminated furrow sediment loss on Portneuf silt loam; application of 10 g m^{-3} (10 ppm) PAM (per unit of water) during the first 2 hr of the irrigation reduced sediment loss from treated furrows by 97 percent. The authors hypothesized that PAM increased the cohesive forces between soil particles in a thin layer at the soil surface. This makes surface soil more resistant to shear forces exerted by the flowing water and decreases the rate of soil removal along the wetted perimeter.

Overland flow applies shear forces to the soil surface which causes particle detachment and movement. As flow velocities increase, shear forces increase and eventually exceed the shear stress required to overcome the cohesive forces between soil particles. As the water infiltrates the soil, sediments suspended in the flow deposit at the furrow surface to form a thin depositional layer, or seal (Segeren and Trout, 1991). The seal conductivity values of the Portneuf silt loam reached values 0.1 to 8% of the conductivity of the soil underlying the seal (Segeren and Trout, 1991). Soils with less than 20% clay, like Portneuf, are most sensitive to seal formation (Ben-Hur et al., 1985). If furrow erosion is curtailed, depositional seal formation may be reduced and high infiltration maintained. All else being equal, a furrow with the highest infiltration rate will have relatively low sediment loss because of decreased runoff and lower flow velocities.

PAM may also affect furrow erosion via impacts on flow rate and sediment size and density. Helalia and Letey (1988a) measured viscosity of water containing 0-50 g m^{-3} (0-50 ppm) PAM in laboratory-prepared solutions and reported that water viscosity was unaltered throughout the range of PAM concentrations tested. Consequently, viscosity at low PAM concentration should not effect flow erosivity. PAM also flocculates flow-suspended clays and silts (Aly and Letey, 1988), and stabilizes aggregated sediment (Terry and Nelson, 1986). Aggregates and sediment flocs are less easily transported in the stream; and the probability of their deposition downstream is greater than for dispersed sediment (Meyer, 1986). Shainberg and Singer (1985) reported that greater clay dispersion results in the formation of a more impermeable depositional seal on the soil surface, whereas seals formed from flocculated particles have an open structure that is highly permeable.

Polymer adsorption on soils is a function of soil, polymer, and solvent (water) characteristics (Wallace et al., 1986; Aly and Letey, 1988; Shainberg et al., 1990). Adsorption of PAM on clay minerals varies with polymer charge type and density. For montmorillonite, Aly and Letey (1988) reported the general order of adsorption to be: cationic > neutral > anionic. As charge density of cationic polymers increases, adsorption increases; but, as charge density of anionic PAM increases, adsorption on montmorillonite decreases (Aly and Letey, 1988). Adsorption of PAM on whole soils will vary because they are comprised of several mineral constituents. The following adsorption relationships were observed for the Arlington soil; its dominant clay minerals include mica, vermiculite, and kaolinite. The relationship between charge-type and polymer adsorption, and the relationship between charge-density and cationic-polymer adsorption onto the soil, was similar to those associated with montmorillonite. However, the effect of charge-density on adsorption of anionic polymers onto the soil differed from that for montmorillonite. The order of adsorption for anionic polymer onto soil (with respect to charge density) was: medium > high > low (Malik and Letey, 1991; Nadler and Letey, 1989). Nadler and Letey (1989) also found that organic matter decreased anionic polymer adsorption on soils.

The activity of the polymer when mixed with soil-water suspensions is not necessarily correlated with adsorption characteristics. In their experiments with montmorillonite clay suspensions, Aly and Letey (1988) found that the flocculating capacity of the polymers was positively correlated to polymer adsorption, but was also influenced by dispersion phase chemistry (water quality). In contrast, Helalia and Letey (1988a) found that adsorption of very-low-charge-density anionic PAM on Arlington soil was less than that of medium-charge-density anionic PAM, yet the very-low-charge anionic polymer proved to be more effective as a soil flocculating agent. Similarly, the low-charge anionic PAM was most effective for forming stable soil aggregates (Nadler and Letey, 1989).

In view of the complexity of polymer-soil interactions, we tested the hypothesis that polymer charge type and density influences PAM's ability to reduce sediment loss from furrows during irrigation. If PAM's performance hinges on its ability to flocculate suspended sediment and form stable aggregates, then the order of effectiveness should be: neutral ~ cationic >> anionic.

METHODS AND MATERIALS

The study area was a 0.6 ha (1.5 ac) field located near Kimberly, Idaho; the soil was the highly erodible Portneuf silt loam (coarse-silty, mixed, mesic, Durixerollic Calciorthid); slope was 1.5%. The study was conducted in 1992 on a conventionally prepared and planted field of silage corn (*Zea mays L.*). The field was disked after the previous season's corn harvest. In spring, the seedbed was prepared with disk and roller-harrow; corn was conventionally planted at 62,000 plants ha^{-1} (153,140 plants ac^{-1}) on 76 cm (30 in) rows. Snake River water was used for irrigation; average electrical conductivity is 0.5 dS m^{-1}, and SAR is 0.06 (Carter et al., 1973).

Furrows were formed as an integral part of the planting operation using weighted furrow forming tools on a rear tool bar. Furrows were shaped by a narrow cultivator shovel followed by a 75 degree, 20 cm deep (approximately), V-shaped boat. Tractor wheels passed in alternate furrows during planting and cultivations; only these trafficked furrows were monitored to eliminate infiltration variation from wheel compaction. Irrigation water was applied from individually regulated valves on gated pipe. Furrows were 175 meters (574 ft) long. Irrigations were 12 h in duration. Inflow rate was 22.7 L min^{-1} (6 gpm) during the initial advance of water (about 1 hr) and 15.1 L min^{-1} (4 gpm) for the remainder of the irrigation. Water application to each furrow was periodically measured.

The study employed a randomized block design with three replications. Seven PAM treatments of different charge type and density were tested. An eighth treatment was the control. The polymers employed are commercially available polyacrylamide (PAM) formulations, manufactured by American Cyanamid Company (Wayne, NJ) and marketed under the trade name Magnifloc[1]. All had high molecular weights, but we were unable to obtain a set of polymers that were identical in this regard. Polymer characteristics are listed in Table 1.

Lentz et al. (1992) obtained a very large reduction in furrow sediment loss by applying PAM at 10 g m^{-3} (10 ppm) during the first 2 hr of the irrigation. In order to highlight potential differences in polymer performance and improve experimental logistics, we applied each PAM treatment at 10 g m^{-3} (10 ppm) for only the initial 0.5 hr of each irrigation. Desired treatment concentrations were achieved by metering an appropriate quantity of polymer stock solution (1200 g m^{-3}) into irrigation water at each furrow head. Two additional 0.63 L applications of stock solution were applied over a 10 min period (~5 g m^{-3} in furrow water) at 4 and 8 hrs into the irrigation. The total PAM application was 0.257 kg ha^{-1} (1.4 lb ac^{-1}). PAM application times were lengthened to treat the entire advance phase (~ 60 min) of the seventh irrigation. Rates of irrigation inflow and polymer injection were monitored during the experiment to ensure constancy.

Furrows were irrigated seven times during the growing season. Inflow and outflow rates, and sediment concentration were measured for all irrigations. Freshly formed furrows were irrigated in irrigations 1 and 3, and previously irrigated (repeat) furrows were treated in others. Irrigations 2 and 4 were not treated in order to observe potential residual impacts of a previous PAM application. Information concerning each irrigation is presented in Table 2. Acrolein, a moss herbicide, was added to irrigation water by the canal district during much of the third irrigation. Data from this irrigation were excluded from the analysis since the organic material may have had a nonuniform influence on activities of the different polymers.

Irrigation and runoff start times were noted in all irrigations. Runoff rates were measured at least hourly with calibrated V-notch flumes. The flumes,

Table 1. Treatment and Product Codes, and Properties of Polyacrylamides Employed in the Study.

Treatment Code	MAGNIFLOC Designation	Charge Type	Charge Density (mole %)	Molecular Weight (Mg/mole)
PAM-A-35	835A	Anionic	35	15
PAM-1-18	836a	Anionic	18	15
PAM-A-7	837A	Anionic	7	15
PAM-N-0	905N	Neutral	0	15
PAM-C-10	492C	Cationic	10	6
PAM-C-20	494C	Cationic	20	6
PAM-C-30	496C	Cationic	35	6

Table 2. Time, Furrow Conditions, and Treatment Rates for Each Irrigation.

Irrigation Number	Date (1992)	Furrow Condition†	PAM Application Rate‡ (conc., initial and supplemental)
1	June 4	Freshly formed	10 g m^{-3}, 30 min. initial + interm.
2	June 18	Repeat	0
3	July 15§	Freshly formed	10 g m^{-3}, 30 min. initial + interm.
4	July 29	Repeat	0
5	August 12	Repeat	10 g m^{-3}, 30 min. initial + interm.
6	August 19	Repeat	10 g m^{-3}, 30 min. initial + interm.
7	August 26	Repeat	10 g m^{-3}, Full advance (~60 min.)

† Furrows were formed on June 1, and cultivated and reformed on July 10. Repeat furrows were undisturbed since the last irrigation.

‡ Initial application began when flow commenced. Supplemental, intermittent applications (~5 g m^{-3} PAM for 10 min) were made at 4 and 8 hrs into irrigation.

§ Acrolein (moss herbicide) present in irrigation water.

originally developed and calibrated by Robinson and Chamberlain (1960) satisfy the hydraulic requirements for long-throated flumes (Bos et al., 1984). Net furrow infiltration was determined from the difference of inflow and runoff volumes.

One-liter runoff samples were collected from free-flowing flume discharge at each flume reading. Samples were collected every 30 min during the first 2-3 hr of the runoff and every 60 min thereafter. The weight of sediment per liter of runoff was determined from the settled volume of sediment in Imhoff cones (Sojka et al., 1992), by calibrating the volume of settled sediment and sediment weight per unit volume of runoff (R^2 = 0.99 for >0.5 g l^{-1}). The Duncan multiple comparison procedure examined sediment-loss mean separations ($P < 0.05$) for treatments in each irrigation.

RESULTS AND DISCUSSION

Data from repeat furrows, treated with 30-min PAM applications (Irrigations 5 & 6), indicated no significant differences between any of the treatments (data not included). Large variability among furrows partially accounts for the lack of discrimination between treatments in Irrigations 5 and 6. We surmised that the 30-min treatment period employed was not sufficient in these consolidated furrows to impact sediment loss. PAM treatment was extended over the entire furrow advance (~ 60 min) in the seventh irrigation in order to test this hypothesis.

Influence of Charge Type

Sediment loss data from treated furrows, for fresh and repeat conditions, show that charge type had a significant influence on the PAM's efficacy. Charge type had no significant influence on residual efficacy of PAM treatments, i.e. carry over effects from a treated irrigation to the following nontreated irrigation could not be discriminated. Sediment loss values grouped by PAM charge type are presented in Figure 1. Data from fresh furrows (Irrigation 1) demonstrate that neutral or anionic PAMs were about twice as effective as cationic forms for reducing sediment loss from furrows. In Irrigation 7 (repeat furrows, 60 min applications) sediment loss from control furrows did not differ statistically from PAM treated furrows; however, sediment reduction when using the anionic PAM was significantly greater than when cationic forms were used.

Inferior performance of cationic PAMs may have resulted, in part, from their lower molecular weights. Molecular weight of polymers influences adsorption

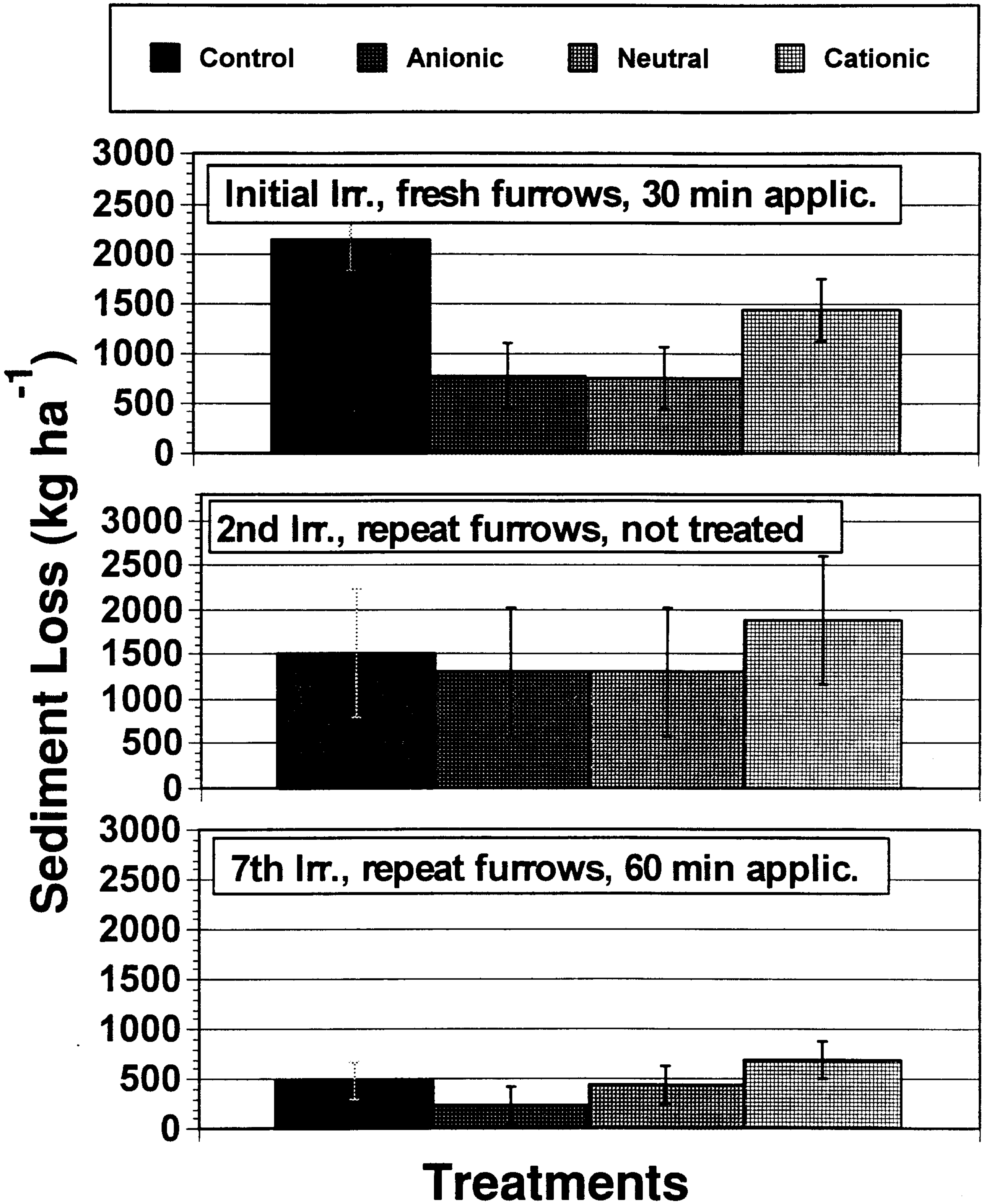

Figure 1. Sediment loss for PAM charge types in the first, second and seventh irrigations. (Error bars represent 95% confidence intervals.)

and flocculation processes. In general, as the molecular weight increases, polymer adsorption increases (Lee and Somasundaran, 1989). The relation between molecular weight and flocculation is less generalizable because the polymer molecular weight at which maximum flocculation occurs differs depending on the polymer and adsorbent (LaMer and Healy, 1963); however, polymer activity often increases with increasing molecular weight.

The apparent decrease in efficacy of PAM treatments in Irrigation 7 may have been due to decrease in the erodibility of the furrows as the season progressed. Aggregate stability of Idaho soils has been shown to increase through the growing season (Bullock et al., 1988), and crop root growth during the summer can stabilize the furrow soils (Kemper et al., 1985). As the season progressed, residue that sloughed into furrows from corn plants also reduced the furrow erosion potential (Aarstad and Miller, 1978). Protection afforded soils by PAM treatments was less important under these circumstances, making differences between treated and control furrows more difficult to verify.

During Irrigation 2, within-treatment sediment loss variability (repeat furrow, nontreated), was larger than in treated Irrigations 1 and 7. As a result, no significant differences between PAM treatments, or between the control and PAM treatments were observed. Thus, no residual PAM effects carried over from the previous treated irrigation. This may have resulted from the abbreviated PAM application period (30 min) employed in the previous treated irrigation. Lentz et al. (1992) observed residual potency in PAM treated furrows, but they applied PAM during the entire furrow advance. Lentz et al. (1992) noted that variability of sediment loss values increased in subsequent untreated irrigations in which the residual protection of PAM treatments began to fail. A similar phenomenon may have occurred in Irrigation 2.

Influence of Charge Density

Cationic or anionic PAM treatments having high charge densities appeared to be more effective for reducing sediment loss from furrows than low-charge density polymers. Sediment loss data for charge density treatments are presented in Figure 2. Differences between treatments are less discernable than in the previous analysis because treatment sample numbers are lower. Differences between anionic charge density treatments in Irrigations 1, 2, or 7 were not significant. However, average sediment loss for the high-charge anionic PAM treatment in both Irrigations 1 and 7 was lower than its low-charge counterparts. Additionally, in Irrigation 7, the high-charge anionic PAM treatment was the only one that had a significantly lower sediment loss than the control. Similarly, statistical analysis detected no significant differences between cationic charge density treatments. The trends in sediment loss between these treatments suggests that, overall, the high-charge density cationic PAM was more effective than cationic PAMs for reducing sediment loss in furrows.

CONCLUSIONS

This investigation demonstrated that both charge type and density affect the capacity of PAM to control sediment losses in irrigated furrows. On Portneuf soils, the order of effectiveness for PAM charge type was: anionic > neutral > cationic. Within anionic and cationic charge types, PAM efficacy appeared to increase with increasing charge density. Dominant clay minerals in Portneuf soils include smectites (montmorillonite) and hydrous micas. Previous research indicates that the order of flocculation for this soil (with respect to charge type) should be: cationic > neutral > anionic. This is the reverse order of what we observed for furrow sediment loss. These relationships suggest that PAM capacity to reduce sediment loss in irrigated furrows is not primarily associated with its ability to flocculate flow-suspended soil particles or form stable soil aggregates. This lends support to the hypothesis put forward by Lentz et al. (1992) who surmised that PAM reduced sediment loss from furrows by increasing surface soil cohesion along the furrow's wetted perimeter.

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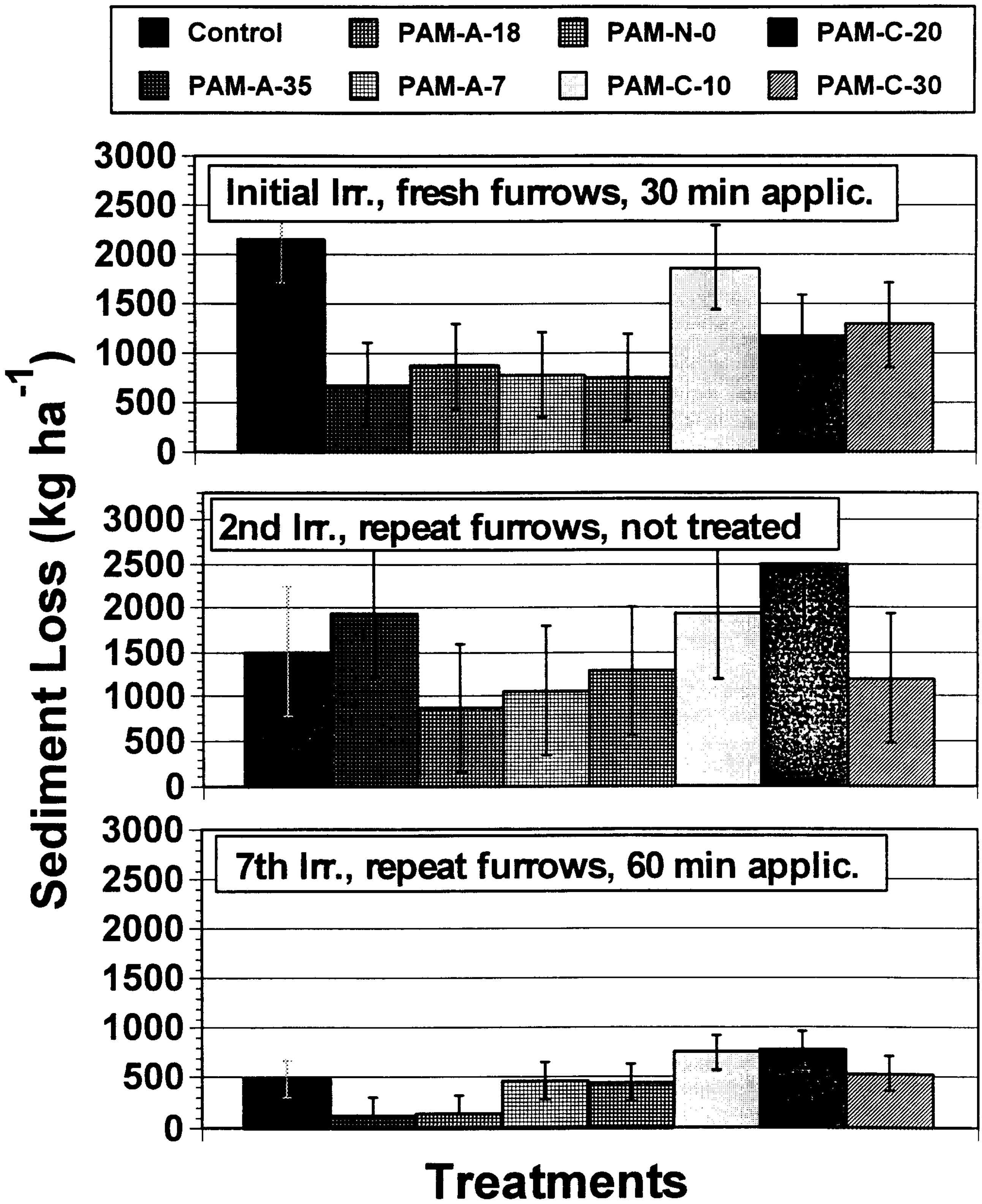

Figure 2. Sediment loss for each treatment in the first, second, and seventh irrigations. (Error bars represent 95% confidence intervals.)

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