Weed seed transport and weed establishment as affected by polyacrylamide in furrow-irrigated corn

R.E. Sojka, D.W. Morishita, J.A. Foerster, and M.J. Wille

ABSTRACT: Polyacrylamide (PAM) has been used successfully to reduce erosion and increase infiltration on nearly a half million hectares of United States irrigated farmland. PAM is a potent and environmentally safe flocculent that greatly accelerates separation of suspended solids from water. It also improves particle cohesion, stabilizing soil structure. We hypothesized that in irrigation furrows, PAM prevents loss of weed seed and might affect weed establishment and management practices. We grew corn (*Zea mays L.*) in plots without herbicides, or that were treated with either Eradicane® (EPTC + dichlormid) or Dual® II (S-Metolachlor) and irrigated in furrows that had either no PAM, or that were treated either with 10 g m^{-3} (10 kg ML^{-1} or 10 ppm) dissolved PAM during water advance, or with PAM applied as a powder patch at the furrow head. As in previous studies, erosion was greatly reduced with PAM and infiltration was increased. PAM use also reduced runoff loss of weed seeds (barnyardgrass, kochia, redroot pigweed, common lambsquarters, and hairy nightshade) 62% to 90%. Interactions of herbicide treatments and PAM on erosion, infiltration, and weed seed loss were related to the mulching effect of weed vegetation. PAM is an effective and environmentally safe means of reducing weed seed distribution in furrow irrigation water while simultaneously reducing erosion and increasing infiltration in weed-free crop production.

Keywords: Dichlormid, EPTC, erosion, infiltration, metolachlor, return flows, runoff, seed bank, surface flow, water quality

In the 1990s, water-soluble polyacrylamide (PAM) was found to be a highly effective and inexpensive erosion-preventing and infiltration-enhancing polymer, when applied at rates of up to 10 kg ML^{-1} (10 ppm or 10 g m^{-3}) in the initial advance of furrow irrigation water across irrigated fields (Lentz et al., 1992; Lentz and Sojka, 1994; McCutchan et al., 1994; Trout et al., 1995; Sojka and Lentz, 1997; Sojka et al., 1998a,b). PAM works by stabilizing soil surface structure and pore continuity and flocculating suspended solids. In 1995, the U.S. Department of Agriculture, Natural Resources Conservation Service (USDA-NRCS) published a practice standard, which was revised in 2001 (Anonymous, 1995, 2001), giving considerations and methods for PAM use. Polyacrylamides were first sold for irrigation erosion control in 1995. By 1999, about 400,000 hectares (1 million acres) were PAM-treated in the United States. Market growth is expected to continue since PAM is one of the most effective and economical technologies

Robert E. Sojka and **James A. Foerster** are with U.S. Department of Agriculture - Agricultural Research Service, Northwest Irrigation and Soils Research Lab in Kimberly, Idaho. **Donald W. Morishita** and **Michael J. Wille** are from the University of Idaho, Twin Falls Research and Extension Center in Twin Falls, Idaho.

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that can improve runoff water quality from irrigated land sufficiently to meet water quality improvements mandated by Federal legislation and court actions.

PAM is most commonly applied to irrigated furrows via two methods; either by dissolving PAM in irrigation water before it enters the furrow, or by placing a small patch of powder directly on the ground in the first 1 to 2 meters (3 to 6 feet) of the furrow before introducing the water. Using the dissolved PAM method reduced sediment in runoff 94% in three years of furrow irrigation studies in Idaho (Lentz and Sojka, 1994). The 1995 USDA-NRCS standard calls for dissolving 10 kg ML^{-1} (10 ppm or 10 g m^{-3}) PAM in furrow inflow water as it first crosses a field (water advance—typically the first 10% to 25% of an irrigation duration). PAM dosing is halted when runoff begins. Dissolved PAM, applied only during advance, prevents erosion throughout a twenty-four hour irrigation. Application amounts under the standard are 1 to 2 kg ha^{-1} (1 to 2 lb ac^{-1}). Lentz and Sojka (1999) reported that effectiveness of applying dissolved PAM at a uniform inflow concentration on new furrows varied with inflow rate, PAM concentration, duration of furrow exposure, and amount of PAM applied. On 1% to 2% slopes, erosion control with PAM was similar for three dissolved PAM application methods: 1) the 10 kg ML^{-1} (10 ppm) during advance USDA-NRCS standard, 2) application of 5 kg ML^{-1} (5 ppm) during advance, followed by 5 to 10 minutes of 5 kg ML^{-1} (5 ppm) reapplication every few hours, or 3) continuous application of 1 to 2 kg ML^{-1} (1 to 2 ppm). Constant application of 0.25 kg ML^{-1} (0.25 ppm) controlled erosion about one-third less effectively than these other three methods. Adequate performance of anionic PAMs also depends on the presence of about 0.5 mM Ca^{++} in the irrigation water (Orts et al., 2001; Wallace and Wallace, 1996).

Furrow irrigators often use a simple application technique, which they call the "patch method." This involves spreading dry PAM granules along the first 1 to 2 m (3 to 6 ft) of the furrow bottom immediately below the inflow point. The amount of granules applied is estimated on an area-equivalent basis, based on furrow spacing × length at a 1 kg ha^{-1} (1 lb ac^{-1}) field application rate. Typical patch doses are 15 to 30 g/furrow (approximately one-half ounce to an ounce, or teaspoon to tablespoon amounts). When water flows over this "patch" of dry granules, a thin, slimy, hydrated polymer mat or film forms that slowly dissolves during the course of the irrigation. Erosion and infiltration effects of the patch method are comparable to dosing the inflow with 10 kg ML^{-1} (10 ppm) dissolved PAM (Sojka and Lentz, unpublished data). The patch method is recognized in the 2001 revision of the USDA-NRCS PAM standard (Anonymous, 2001). Advantages and disadvantages of each application method depend on field conditions and system requirements (Sojka et al., 1998c).

Furrow stream advance is usually slower on loamy or clay soils for a given inflow rate when using 10 kg ML^{-1} (10 ppm) or lower PAM concentrations (Sojka et al., 1998a,b). Surface seals form on untreated furrow channels due to destruction of soil aggregates during rapid wetting, allowing detachment, transport and redeposition of fine sediments in the furrow stream. A seal blocks pores at the soil surface, reducing the surface hydraulic conductivity and infiltration rate of the furrow bottom. Profile pore continuity is better maintained to the soil surface when aggregates are stabilized by PAM. Infiltration on PAM-treated furrows is typically 15% to 50% more, compared to untreated water (Sojka et al., 1998a). Sojka et al. (1998a) reported that infiltration at 40 mm (1.6 in) tension varied among irrigations over the range 12.9 to 31.8 mm hr^{-1} (0.5 to 1.3 in hr^{-1}) for controls and 26.7 to 52.2 mm hr^{-1} (0.9 to 2.1 in hr^{-1}) for PAM-treated furrows and that infiltration at 100 mm (3.9 in) tension varied from 12.3 to 29.1 mm hr^{-1} (0.5 to 1.2 in hr^{-1}) for controls and 22.3 to 42.4 mm hr^{-1} (0.9 to 1.7 in hr^{-1}) for PAM-treated furrows. Because PAM prevents erosion of furrow bottoms (which lowers the furrow stream elevation) and sealing of the wetted perimeter, lateral water movement increases about 25% in silt loam soils, compared to nontreated furrows (Lentz et al., 1992; Lentz and Sojka, 1994). This can be a significant water conserving effect for early irrigations that only need to wet seeds or seedlings and not fill an entire profile.

The flocculating properties of PAM in irrigation water are not restricted to attraction of mineral particles. A recent series of studies demonstrated that broad categories of microorganisms—including algae, bacteria, and fungi—carried across and among furrow-irrigated fields by furrow streams, runoff, and return flows, are reduced by PAM in irrigation water (Sojka and Entry, 1999, 2000; Entry and Sojka, 1999). These results have significant economic and environmental implications, since they point to potential improved microorganism management that could benefit crop production, reduce pesticide use, and improve the hygiene of surface waters affected by agricultural sources of organism contamination. The combined PAM effects on erosion control, infiltration patterns, and microbe sequestration led us to speculate that weed seed movement in furrow irrigation water and weed germination, establishment, and growth might also be affected, both by the sequestration of seed and by the difference in infiltration amount and pattern. Again, economic and environmental implications could be significant.

The importance of preventing the transport and spread of weed seed, various microorganisms, and "trash" in surface irrigation systems was recognized in the 1980s when several mechanical approaches to removal of trash and weed seed from surface irrigation sources were developed (Humpherys, 1983, 1984, 1985; Bondurant and Kemper, 1985; Kemper et al., 1986). Surface irrigation waters commonly carry moss, algae, sago pondweed (*Pomatogeton pectinatus* L.), and seeds of virtually all of the most commonly occurring weeds that infest production fields. In the Pacific Northwest some of the more important weed seeds include, but are not limited to barnyardgrass (*Echinochloa crus-galli* L.), kochia (*Kochia scoparia* L. Schrad.), redroot pigweed (*Amaranthus retroflexus* L.), common lambsquarters (*Chenopodium album* L.), and hairy nightshade (*Solanum sarrachoides* L. Sendtner). Return flows from eroding fields carry weed seeds back to the general water distribution system, causing downstream fields to be inoculated with the seed during irrigation. Even within a given field, as furrows erode, the weed seed present in that field's weed seed bank are moved from upper field reaches to lower field reaches, spreading any existing weed infestation across the field. Preventing weed seed from moving within a given field, or from being transported among fields in runoff and reutilized return flows, would be a substantial production and environmental benefit.

With this in mind, we established a study in furrow-irrigated silage corn. We hypothesized that PAM treatment would sequester weed seeds and affect the establishment and growth of weeds as a result of the seed sequestration and differences in irrigation water infiltration amounts and patterns. We further hypothesized that these effects might differ depending on the mobility of the preplant incorporated herbicide used to control the weeds.

Table 1. 1997 and 1998 season totals for hydraulic parameters for the four intensively monitored irrigations.

Pooled Treatment	Runoff (mm)		Infiltration (mm)		Advance Time (min)	
	1997	1998	1997	1998	1997	1998
Metolachlor	138a	105a	131a	195a	54a	121a
EPTC	136a	110a	132a	190a	55a	120a
None	124a	109a	144a	191a	57a	106a
No PAM	139a	128a	129a	172b	49a	83b
NRCS Std PAM	130a	98b	138a	202a	59a	135a
PAM Patch	129a	98b	139a	202a	58a	128a

Significant differences, at P<.05, indicated within a column and for major treatment groupings (separated by horizontal lines). USDA-NRCS standard refers to the application of 10 ppm dissolved PAM during water advance in the furrow. PAM Patch refers to the application of 28 g of dry PAM granules on the soil in each treated furrow immediately below the inflow spigot.

Methods and Materials

The experimental field was near Kimberly, Idaho on a Portneuf silt loam soil—coarse-silty, mixed, superactive mesic Durinodic Xeric Haplocalcid. The surface diagnostic horizon of this soil has 100 g kg^{-1} (10%) clay, 700 g kg^{-1} (70%) silt, and 10 to 13 g kg^{-1} (1.0% to 1.3%) organic matter. Soil cation exchange capacity (CEC) is 190 mmol$_c$ kg^{-1}. Electrical conductivity of the saturated paste extract (EC) is 0.07 S m^{-1}. The exchangeable sodium percentage (ESP) is 1.5%, with a pH of 7.7 and a calcium carbonate equivalent of 5%. Plots were sloped 1.5% and every other furrow was a wheel tracked furrow used for irrigation.

Corn (Pioneer® brand 3211 in 1997 and Pioneer® brand 3751 in 1998) was planted in six row plots 166 m (545 ft) long. Corn row spacing was 0.76 m (30 in). Planting was on May 8, 1997, and May 6, 1998, using a seeding rate of 79,500 kernels ha^{-1} (32,000 kernels ac^{-1}) each year. May 1 to June 30 rainfall totals were 58 mm (2.3 in) in 1997 and 138 mm (5.4 in) in 1998. In 1997, three noteworthy rainfall events occurred: 7 mm (0.3 in) on May 20, 13 mm (0.5 in) from June 4 through 8, and 25mm (1.0 in) from June 10 through 13. In 1998, four noteworthy rainfall events occurred: 86 mm (3.4 in) from May 8 through 16, 7 mm (0.3 in) from June 2 through 5, 7 mm (0.3 in) from June 15-18, and , 16 mm (0.6 in) from June 22 through 25. Monthly mean temperatures for the two growing seasons were: 1997; May - 16 °C (61 °F), June - 17 °C (63 °F), July - 20 °C (68 °F), August 21 °C (70 °F); and 1998; May 12 °C (54 °F), June 15 °C (59 °F), July 23 °C (73 °F), and August 22 °C (72 °F).

Plots were furrow-irrigated with either: 1) untreated canal water, 2) water containing 10 ppm PAM during initial advance (USDA-NRCS standard PAM method), or 3) water treated with PAM by placing 35 g (1.2 oz) of a granular PAM product (28 g or 1 oz of active ingredient) along the initial 1 m (3 ft) of furrow immediately prior to initiating irrigation (patch method). The PAM used had a molecular weight of 12-15 Mg mol^{-1}, with an anionic charge density of 18%, available commercially as Superfloc® A-836 from CYTEC Industries Inc.[1]. These PAMs are 80% active ingredient. Stock solutions and dilutions used for furrow dosing with dissolved stock solutions were corrected for the active ingredient (a.i.) percentages. Dissolved PAM treatments were dosed by using peristaltic pumps to meter 2000 ppm a.i. PAM into individual furrows at rates that brought the irrigation stream in each furrow to 10 ppm during dosing. Irrigation water was from the Twin Falls Canal Company, and had an EC of 0.05 S m^{-1} and SAR of 0.5 [mmol$_c^{-1}$]$^{0.5}$.

Herbicide treatments were either: 1) controls, 2) EPTC (S-ethyl dipropylthiocarbamate), or 3) metolachlor (2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-(2-methoxy-1-methylethyl) acetate). Chemical formulations used both years were 72.2 % a.i. EPTC and 86.4% a.i. metolachlor. Herbicides were pre-plant spray applied to soil and immediately followed with light incorporation. Metolachlor and EPTC were applied at 2.24 and 4.6 kg a.i. ha^{-1} (2.0 and 4.0 lb a.i. ac^{-1}), respectively, both years. Following spray application, herbicides were incorporated to approximately 5 cm (2 in) depth with a roller harrow.

Plots were in a randomized split plot design with herbicide treatment main plots and PAM treatment subplots. Statistical analyses of the collected data was done by analysis of variance using the LS Means statement of general linear models (GLM) routine in statistical analysis software (SAS). Where individual treatment interactions were found to be insignificant, data were pooled and comparisons of herbicide treatments and PAM treatments were made separately using the pooled data. Means separation was as least significant difference (LSD) at the 5% level of probability. Because of inadequate homogeneity of variance in the weed seed data (Table 4), as determined by examination of residuals, the weed seed data were subjected to several log and square root transforms and reanalyzed. Improvement in means separation was only observed for analysis of log-transformed barnyardgrass weed seed data. Means separation for transformed barnyardgrass seed data in Table 4 are indicated separately.

Irrigation inflow was closely regulated at each furrow inlet using stopwatches and volume-calibrated buckets. Runoff was monitored using small, individual furrow, calibrated flumes (Robinson and Chamberlain, 1960). Infiltration was determined by inflow-outflow difference. Runoff sediment concentration and accumulated loss were determined using the Imhoff cone technique (Sojka et al., 1992, 1994). The crop was irrigated five times in 1997; on June 10 and 26, July 14 and 31 and August 18. The crop was irrigated six times in 1998; on June 30, July 7, 16 and 30, and August 13 and 28. Inflow, runoff, sediment, infiltration and advance were intensively measured on the first four dates in 1997 and on the first, third, fourth and fifth dates in 1998. Water applied during the four intensively monitored irrigations each year was 268 mm (10.6 in) in 1997 and 300 mm (11.8 in) in 1998. Runoff, infiltration, and advance times for each treatment are presented in Table 1. The average amounts of additional water infiltrated across treatments during the three less intensively monitored irrigations were: 22 mm (0.9 in) on August 18, 1997, and 33 mm (1.3 in) on July 7, 1997; and 18 mm (0.7 in) on August 28, 1998. Because runoff, infiltration, and advance times did not differ at the 5% level across the nine interactive treatments, data were pooled and values are only presented in Table 1 for

Table 2. 1997 and 1998 season total sediment loss for the four intensively monitored irrigations.

Pooled Treatment	Sediment Loss (kg ha^{-1})	
	1997	1998
Metolachlor	5568a	2036a
EPTC	4346a	2239a
None	2318a	2101a
No PAM	9402a	5161a
NRCS STD	1745b	598b
Patch	1085b	617b

Significant differences, at $P<.05$, indicated within a column and for major treatment groupings (separated by horizontal lines). USDA-NRCS standard refers to the application of 10 ppm dissolved PAM during water advance in the furrow. PAM Patch refers to the application of 28 g of dry PAM granules on the soil in each treated furrow immediately below the inflow spigot.

the three herbicide treatment means and for the three erosion water treatment means.

Weed seed losses were determined in separate runoff subsamples on the four intensively monitored dates each year. A 0.5 L (0.13 gallon) runoff water sample was collected corresponding to sediment sampling times. Weed seed from each water sample was separated by pouring the sample into a Buchner funnel and collecting on filter paper. Weed seed were identified and counted from each sample. Weed seedling density was determined by identifying and counting seedlings 7.5 cm (3.0 in) to each side of two-meter (79 in) sections of furrow at three points in the field. Areas of weed seedling counts were located near the top, middle, and bottom of each plot. These two-meter sections were 28, 84, and 140 meters (92, 276, and 459 ft), respectively, from the inflow. Densities were determined four times during the growing season, but only the initial counts are presented.

On September 8 and 21 of 1997 and 1998, respectively, forage yield was measured on two three-meter (9.8 ft) harvest row samples; one from the upper and one from the lower half of each plot. Whole corn stalk samples were harvested from the center two rows of each plot by cutting the stalks at the first above-ground node. Fresh weight of the samples was determined in the field and they were green-chopped with a forage chopper. A portion of the green-chop was collected in large sub-sample bags for moisture determination, which was accomplished by weighing the subsamples fresh and after drying for several days at 50 °C (122 °F).

Results and Discussion

Water and sediment. In both 1997 and 1998, PAM treatment reduced cumulative seasonal runoff and sediment loss, and increased water advance time and infiltration. Mean seasonal totals for the monitored irrigations are presented in Tables 1 and 2. These results parallel findings of numerous previous papers (Lentz et al., 1992; Lentz and Sojka, 1994; McCutchan et al., 1994; Trout et al., 1995; Sojka and Lentz, 1997; Sojka et al., 1998a,b).

Seasonal sediment loss reductions for the dissolved (USDA-NRCS standard) and patch PAM application methods, compared to controls, were 81% and 88% respectively in 1997, and both were 88% in 1998. Herbicide treatment increased cumulative seasonal runoff and sediment loss in 1997, but not in 1998. There was little effect of herbicide treatment on advance time in 1997, but a lengthening of advance time in 1998 compared to controls. Herbicide treatment decreased infiltration in 1997, but had little, if any, effect in 1998.

Herbicide effects on runoff, infiltration, sediment loss, and advance time in 1997 were as expected, with weedy no-herbicide furrows acting as a vegetative mulch. Results in 1998 may relate to delayed stand establishment and poorer weed control by herbicides caused by a cool wet spring.

Weed seedling density. The PAM-treated furrows had 12.7% higher weed seedling densities than nontreated furrows in 1997 (Table 3), but a 5.0% decrease in 1998;

Table 3. 1997 and 1998 first count weed seedlings for the four intensively monitored irrigations.

Pooled Treatments	Kochia	Lambs-quarters	Redroot pigweed	Hairy nightshade	Green foxtail	Barnyard grass	Common mallow	Annual sowthistle	Total
1997 (seedlings meter^{-2})									
Metolachlor	11.5a	7.9a	4.5b	1.7a	0.7a	4.1a	3.3a	0.0a	33.8a
EPTC	9.1a	12.3a	6.4b	3.3a	1.0a	3.6a	5.6a	0.0a	41.3a
None	3.0a	16.2a	13.4a	7.2a	1.7a	7.2a	4.1a	0.0a	52.7a
No PAM	5.7a	12.8a	6.8a	3.8a	0.4a	6.1a	3.8a	0.0a	39.3a
NRCS STD	10.1a	12.2a	9.2a	5.1a	1.5a	4.0a	5.0a	0.0a	47.0a
Patch	7.9a	11.4a	8.3a	3.3a	1.6a	4.9a	4.3a	0.0a	41.6a
1998 (seedlings meter^{-2})									
Metolachlor	4.4a	19.0a	4.7a	25.4a	0.4a	2.7a	0.2a	0.2a	57.0a
EPTC	5.6a	32.3a	17.1a	72.9a	1.1a	4.9a	0.1a	0.2a	134.3a
None	4.4a	35.1a	24.9a	77.2a	4.7a	8.9a	0.2a	0.2a	155.7a
No PAM	4.3a	26.1a	12.9a	67.8a	2.2a	5.8a	0.0a	0.5a	119.6a
NRCS STD	6.2a	29.3a	16.2a	48.9a	2.4a	4.6a	0.4a	0.2a	108.1a
Patch	3.9a	31.0a	17.7a	58.8a	1.6a	6.0a	0.2a	0.0a	119.2a

Significant differences, at $P<.05$, indicated within a column and for major treatment groupings (separated by horizontal lines). USDA-NRCS standard refers to the application of 10 ppm dissolved PAM during water advance in the furrow. PAM Patch refers to the application of 28 g of dry PAM granules on the soil in each treated furrow immediately below the inflow spigot.

Table 4. 1997 seasonal weed seed loss in runoff (seeds ha^{-1}) for the four intensively monitored irrigations

Treatments Herbicide	 PAM	Kochia	Lambs-quarters	Redroot pigweed	Hairy nightshade	Barnyard grass	Common mallow	Total
				1997 (Thousands of Seeds)				
Metolachlor		93a	2,563a	2,790a	210a	42a	53a	5,751a
EPTC		156a	2,392a	2,381a	250a	0a	65a	5,244a
None		101a	1,432a	2,317a	306a	0a	38a	4,193a
	No PAM	210a	3,958a	3,854a	467a	42a	78a	8,609a
	NRCS STD	78a	972b	1,395b	158b	0a*	64a	2,668b
	Patch	62a	1,456b	2,240ab	141b	0a*	13a	3,912b
Metolachlor	No PAM	80a	4,524a	4,568a	440a	126a	49a	9,787a
Metolachlor	NRCS STD	87a	1,450a	894a	75a	0a*	69a	2,576a
Metolachlor	Patch	112a	1,716a	2,909a	114a	0a*	39a	4,890a
EPTC	No PAM	317a	4,592a	3,646a	319a	0a*	71a	8,944a
EPTC	NRCS STD	78a	711a	1,829a	237a	0a*	124a	2,979a
EPTC	Patch	74a	1,872a	1,668a	195a	0a*	0a	3,810a
None	No PAM	234a	2,759a	3,347a	642a	0a*	113a	7,095a
None	NRCS STD	70a	755a	1,463a	161a	0a*	0a	2,449a
None	Patch	0a	781a	2,142a	113a	0a*	0a	3,036a
				1998 (Thousands of Seeds)				
Metolachlor		314a	1,019a	424a	204a	37a	0a	1,998a
EPTC		248a	1,983a	306a	303a	0a	0a	2,840a
None		204a	1,221a	222a	87a	23a	30a	1,786a
	No PAM	686a	3,399a	842a	527a	37a	30a	5,521a
	NRCS STD	28b	292b	75b	30b	0a*	0b	425b
	Patch	52b	530b	36b	37b	23a*	0b	678b
Metolachlor	No PAM	943a	2,102a	1,095a	500a	111a	0b	4,751a
Metolachlor	NRCS STD	0a	371a	130a	32a	0b	0b	532a
Metolachlor	Patch	0a	583a	48a	79a	0b	0b	710a
EPTC	No PAM	607a	5,164a	789a	878a	0b	0b	7,438a
EPTC	NRCS STD	23a	240a	95a	32a	0b	0b	390a
EPTC	Patch	113a	544a	35a	0a	0b	0b	692a
None	No PAM	507a	2,932a	642a	203a	0b	90a	4,374a
None	NRCS STD	60a	265a	0a	25a	0b	0b	351a
None	Patch	44a	465a	23a	32a	69ab	0b	633a

Significant differences, at P<.05, indicated within a column and for major treatment groupings (separated by horizontal lines). Asterisks in the barnyardgrass column indicate letter b when analyzed using a log transform. USDA-NRCS standard refers to the application of 10 ppm dissolved PAM during water advance in the furrow. PAM Patch refers to the application of 28 g of dry PAM granules on the soil in each treated furrow immediately below the inflow spigot.

however, these densities were not statistically different. Each year there was a single cultivation, but while there was seedling density variation among counting dates (data not shown), the general tendency through the season remained similar to the initial weed seedling counts. We believe it is reasonable to expect higher weed densities with PAM treatment since, in the absence of PAM treatment, there was a tendency for erosion to wash away partially germinated seed and small seedlings in control furrows (especially herbicide-treated furrows, which remained bare of any vegetative mulch caused by weeds). Whereas, by contrast, PAM-treated furrows, with soil that was protected against erosion, had a greater tendency to allow germination and emergence to occur.

Weeds germinated in both the no-herbicide treatment and in the two herbicide treatments. With herbicide treatment, however, fewer weeds germinated and weed growth and vigor were reduced in the herbicide treatments compared to the no-herbicide treatments (data not shown). No statistically significant differences in weed species or total seedling densities between herbicide treatments were observed in either year at each measurement time, which was prior to each irrigation. Polyacrylamide treatment did not significantly affect weed seedling densities. Average weed seedling densities in the no-herbicide treatments were 125 and 225 plants m^{-2} (105 and 188 plants per square yard) in 1997 and 1998, respectively.

Weed seed. In 1997 and 1998, weed seed loss in runoff was significantly reduced by PAM use (Table 4). The reduction in 1997 was 69% for the USDA-NRCS standard method and 56% for the patch method (62% average). In 1998, the reduction was 92% for the USDA-NRCS standard method and 88% for the patch method (90% average). In both years, PAM use resulted in consistent numerical reduction in the number of weed seeds in runoff for all species, although the reductions were not consistently statistically significant for individual species. In 1997, PAM signifi-

Table 5. Physical characteristics of weed seed collected in runoff water.[1]

Species	Dimensions	Outline Shape	Surface Characteristics	Average Weight per Seed[2] (mg)
Common lambsquarters	1.1-1.3 mm long, 1-1 mm wide	circular	membranous pericarp often attached; nearly smooth surface without pericarp	22
Redroot pigweed	1-1.5 mm long, 0.6-1 mm wide	circular	very smooth	47
Kochia	1.1-2.1 mm long, 0.9-1.5 mm wide	pear-shaped	very finely roughened	77
Hairy nightshade	1.5-2.0 mm long, 0.9-1.1 mm wide	ovate	finely pitted	74
Common mallow	1.6-1.8 mm long, 1.5-1.7 mm wide	kidney-shaped to nearly round	finely textured	176
Barnyardgrass	2.2-3.0 mm long, 1.6-2.2 mm wide	ovate to oval	lemma and palea usually remain attached; smooth and shiny	133
Green foxtail	1.8-2.2 mm long, 1.0-1.3 mm wide	oval to ovate	lemma and palea often remain attached and appear shiny	138

[1] Physical characteristics compiled from Delorit, (1970).

[2] Individual weights of each species was determined by the average weight of three seed lots containing 100 seed.

cantly reduced weed seed loss for common lambsquarters, redroot pigweed, and hairy nightshade. In 1998 PAM significantly reduced weed seed loss for kochia, common lambsquarters, redroot pigweed, hairy nightshade and common mallow.

Some of the best weed seed sequestration by PAM observed in this study was for barnyardgrass and common mallow. However, sequestration of both species proved highly variable. PAM reduction of barnyardgrass seed in runoff was highly variable in both years, and in 1997, was only significant if data were log-transformed for analysis. Means separation of the other weed seed loss data for individual species were unaffected by log transformation. Clearly, barnyardgrass seed sequestration was best in the control and EPTC treatments in both years of our study. In 1997, seed loss was entirely from the metolachlor no-PAM treatment, and in 1998, was two-thirds from the metolachlor no-PAM treatment, and one-third from the no-herbicide PAM patch treatment. There may be several possible explanations for these patterns. One may be that differences in the timing and depth of erosion occurred between the USDA-NRCS and patch treatments during the monitored treatments in 1998. This could have affected the loss of seed bank seed, or recently deposited seed, favoring collection of barnyardgrass seed in runoff from the no-herbicide patch treatment, and in the metolachlor no-PAM treatment. This may have indicated a greater contribution of seed from weeds established in the year of the study, or an effect of seed stratification in the soil. Alternatively, the broader interpretation of the data could suggest that barnyardgrass seed properties have a greater affinity for sequestration by PAM. A different trend of interest occurred for common mallow seed. In this case, it is likely that the 1997 mallow seed was contained within the eroding soil layer, whereas in 1998, this layer was below the depth of erosion activity in most treatments.

Because there was greatly improved overall weed seed retention (see Total column in Table 4) by PAM in 1998, despite similar sediment loss reductions across PAM treatments and years, it seems likely that PAM effects on weed seed loss are not simply tied to reductions in erosion (i.e. excavation of weed seed from the soil weed seed bank). It is also likely that weed seed retention relates to annual changes in the size and stratification of the weed seed bank in the soil, and possibly, on the soil surface. The data discussed above for barnyardgrass and common mallow seem to support this finding.

The characteristic properties of each weed species' seed (Table 5) may also affect PAM's ability to sequester the seed. Currently, the U.S. Department of Agriculture-Natural Resources Conservation Service (USDA-NRCS) only recommends anionic PAMs for erosion control (USDA-NRCS, 2001), and these materials typically are 12 to 15 Mg mole^{-1}, with 18% negative charge density. Field studies comparing PAM charge type, charge density, and molecular weight effects on erosion control (Lentz et al., 2000) suggest there might also be differences in PAM efficacy for weed seed retention related to these attributes of molecular conformation. The demonstrated dependence of PAM effects on presence of calcium ions (or other bridging cations), and reduced efficacy with high levels of sodium ion, suggest that irrigation water sodium adsorption ratio (SAR) and soil exchangeable sodium percentage (ESP) could also affect weed seed retention (Aly and Letey, 1998; Ben-Hur et al., 1992; El-Morsy et al., 1991; Orts et al, 1999, 2000; Wallace and Wallace, 1996).

The weed seed collected in the runoff water in our study were small, averaging less than 2 mm (0.08 in) in length, with the exception of barnyardgrass, which can be less than 4 mm (0.16 in) long. Redroot pigweed seeds are ovate to circular in outline and lens-shaped with a smooth surface weighing about 0.5 mg (0.000018 oz) each. Common lambsquarters seeds were the smallest collected and the lightest of the group. They are 1.1 to 1.3 mm (0.04 to 0.05 in) long, have a circular outline, often with a membranous pericarp attached, and weigh about 0.2 mg (0.000007 oz) each. Without the pericarp, the seed are nearly smooth. Kochia seed average 1.1 to 2.1 mm (0.04 to 0.08 in) in length with a pear-shaped outline, have a very fine, roughened surface, and each seed weighs about 0.8 mg (0.00003 oz). Hairy nightshade

Table 6. 1997 and 1998 forage yield (Mg ha^{-1}) for the four intensively monitored irrigations.

Pooled Treatment	Adjusted Yield at 70% H_2O 1997	1998
Metolachlor	55a	55a
EPTC	54a	56a
None	53a	52a
No PAM	50b	53a
NRCS STD	55ab	55a
Patch	56a	54a

Significant differences, at $P<.05$, indicated within a column and for major treatment groupings (separated by a horizontal line). USDA-NRCS standard refers to the application of 10 ppm dissolved PAM during water advance in the furrow. PAM Patch refers to the application of 28 g of dry PAM granules on the soil in each treated furrow immediately below the inflow spigot.

seeds are 1.5 to 2.0 mm (0.06 to 0.08 in) long, tend to be flattened, are ovate-shaped, have a finely pitted surface, and weigh 0.7 mg (0.000025 oz) each. Common mallow seed are 1.6 to 1.8 mm (0.06 to 0.07 in) long, kidney-shaped to nearly round with a small well-defined notch on the margin, and are the heaviest, weighing about 1.8 mg (0.000063 oz) each. The seed surface is finely textured. Barnyardgrass average 2 to 2.3 mm (0.08 to 0.09 in) in length and weigh about 1.3 mg each (0.000046 oz). They are elliptical in shape with a long tapered apex. The surface of the lemma and palea, which usually remain attached, is smooth and shiny. Green foxtail seed are similar to barnyardgrass in that the lemma and palea also usually remain attached to the seed and are elliptical in shape. Slightly smaller than barnyardgrass, green foxtail seeds are 1.8 to 1.9 mm (0.07 to 0.08 in) long, and weigh about 1.4 mg (0.00005 oz) each.

It does not appear that herbicide treatment influenced weed seed loss as much as the PAM treatment, since there were fewer differences between herbicides in seed loss among weed species. While the specific interactions are not yet completely understood, it is clear that PAM is highly effective at reducing the migration of weed seed from one point in the field to another in the flowing furrow stream, or from one field to another in runoff that is utilized for irrigation downstream.

Yields. Forage yields were similar among years and all treatments (Table 6). In this study, weed control until canopy coverage was reasonably good in all treatments as a result of conventional cultivation. Thus, forage yield was not affected by weed control treatment in either year. Irrigation was adequate among treatments as well, therefore, the increased infiltration was not greatly expressed as yield. Some loss of nitrogen may have occurred with increased infiltration, partially negating the yield advantage of improved infiltration.

Summary and Conclusion

PAM is a highly effective, easy, and inexpensive erosion control method used on nearly a half-million hectares of furrow-irrigated agriculture in the United States. The practice is rapidly gaining greater acceptance. Our data show that PAM use reduces weed seed migration in runoff water, suggesting that, as PAM is used more extensively, there may be reductions in weed seed migration within fields and at a watershed scale in surface irrigation schemes. That effect could substantially reduce the spread of weeds, ultimately reducing the need for certain herbicide treatments, particularly as technology becomes available to better allow site-specific application of herbicides for weed control. PAM use has already been shown to reduce the loss of soil-incorporated herbicides in runoff water by direct and indirect effects associated with prevention of sediment detachment and loss (Agassi et al., 1995).

It is also apparent from our data, however, that PAM's soil stabilization may improve the chances for weed germination within the irrigated furrow, even where preplant incorporated herbicides have been applied. This suggests that PAM use may require greater attentiveness to lay-by cultivation or over-the-top herbicide application for effective season-long weed control. The effect of weeds on yield in this silage corn crop was minimal.

There is another positive aspect to the interpretation of our data relating to the use of polyacrylamides beyond irrigated agriculture. PAM is being used increasingly for construction site erosion control and for roadway and road cut stabilization, as well as an additive for hydro-seeding of steep slopes. Roa-Espinosa et al. (2000) found that regardless of application method, PAM mixed with seed and mulch was effective in reducing sediment yield by up to 93% in test plots. Their most effective treatment was mixing PAM with mulch, seed, and lime applied to dry soil, and the treatment was far less expensive than standard construction site erosion prevention treatments. While the work of Roa and others have met great interest in the construction and highway industry, questions have persisted as to what direct effect the PAM had on grass or other cover seed germination and performance. Our data would suggest that PAM does not impair seed germination, and that PAM protects bare soil from erosion while germinating seed becomes established, eventually providing a vegetative ground cover. This is precisely the strategy used in hydroseeding and in various construction site PAM applications.

There is much yet to learn about PAM interactions with agricultural weed control strategies. Ongoing new work with edible dry beans suggests that the effects of the weed populations are more important in the presence of a less competitive crop canopy. The impact of PAM use on weed seed bank dynamics will need to be more closely investigated to fully understand and best exploit these effects for improved weed control and reduction of herbicide use. In short, the agronomics of PAM use related to weed control seem to be very positive, but how to best optimize the concurrent use of PAM with herbicides and other weed control strategies requires considerable further study.

Endnote

[1] Mention of trademarks, proprietary products, or vendors does not constitute a guarantee or warranty of the product by the U.S. Department of Agriculture-Agricultural Research Service and does not imply its approval or endorsement to the exclusion of other products or vendors that may also be suitable.

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