THE EFFICACY OF POLYACRYLAMIDE TO REDUCE NUTRIENT MOVEMENT FROM AN IRRIGATED FIELD

J. A. Entry, R. E. Sojka

ABSTRACT. *Irrigation–induced erosion contributes to elevated sediment and nutrient concentrations in irrigation return–flow water. Polyacrylamide (PAM) is an effective flocculent widely used to reduced soil erosion. We hypothesized PAM would reduce transport of sediment and nutrients in surface irrigation water flowing over soil. We measured nutrients in irrigation inflow and runoff water and total and extractable nutrients in sediment transported from agricultural fields. Treatments were:(1) PAM application and no PAM (control), (2) three flow rates (7.5, 15.0, and 22.5 L min*$^{-1}$*), (3) distance along the furrow (1 m below the inflow point and 40 m down furrow), and (4) time during irrigation (0.5, 3.5, and 6.5 h after initial inflow). After irrigation water flowed 40 m, water flowing in furrows receiving PAM treatments reduced the* NO_3^- *concentration in runoff by 85% and the total P concentration in water by 90% compared to runoff water in furrows without PAM, regardless of flow rate. Mass export of* NH_4^+*,* NO_3^-*, dissolved reactive phosphorus (DRP), total P, K, Ca, Mg, Fe, Mn, Cu, B, and Zn in untreated irrigation runoff water increased as the flow rate increased from 7.5 to 22.5 L min*$^{-1}$*. Export of these nutrients, via sediment carried by untreated irrigation runoff water, increased from 2 to 5 fold as the flow rate increased from 7.5 to 22.5 L min*$^{-1}$*. After water flowed 40 m, transport of these extractable nutrients was reduced from 10 to 40 fold in PAM–treated furrows. With proper application, PAM reduces nutrient loss from furrow–irrigated agricultural fields, protecting surface water and groundwater quality.*

Keywords. *Irrigation, Nitrogen, Phosphorus, Runoff, Water Quality.*

Irrigation–induced erosion contributes to elevated nutrient concentrations in irrigation return flows (Brown et al., 1974, Carter et al., 1974; Sojka, 1998; Trout and Neibling, 1993; Bjorneberg et al., 1998). Elevated nutrient concentrations in irrigation runoff cause nutrient accumulation in aquatic environments such as lakes, streams, and wetlands (David and Gentry, 2000; Edwards et al., 2000; Sharpley et al., 2000). Most aquatic ecosystems develop in conditions limited by nitrogen (N) and phosphorus (P). Changes in flora and fauna have been attributed to increased input of nutrients (Davis, 1991; Koch and Reddy, 1992; Cooper and Brush, 1993; Stevenson et al., 1993). Increased N and P in wetland ecosystems often leads to eutrophication, creating an abnormally high oxygen demand, depleting the aquatic oxygen supply, and often resulting in the death of many aquatic organisms (Cooper and Brush, 1993).

Polyacrylamide (PAM) is used in furrow–irrigated agriculture for erosion control and increased infiltration (Lentz et al., 1992; Lentz and Sojka, 1994; Sojka et al., 1998a, 1998b). PAM can be mixed into irrigation water or spread on the soil as a patch. Both types of treatments greatly reduce the sediment loss rate over time, dissolved reactive phosphorus (DRP), and total P and NO_3^- concentrations (Lentz et al., 1998; Entry and Sojka, 2000; Lentz et al., 2000). In a three–year series of studies conducted on silt loam soils, runoff sediment reduction averaged 94% and infiltration increased 15% (Lentz et al., 1992; Lentz and Sojka, 1994; Lentz et al., 1998). Additional studies further documented the capacity of PAM treatment of furrow irrigation water or spread on the soil as a patch to reduce sediments, nutrients, dissolved organic carbon (DOC), microorganisms, and pesticides in irrigation runoff (Sojka et al., 1998a, 1998b; Entry and Sojka, 2000; Sojka and Entry, 2000; Lentz et al., 2001; Entry et al., 2002).

The most frequent approach in furrow irrigation studies involved PAM treatment of the furrow advance stream. Efficacious treatment was usually possible with PAM application rates of about 1 kg ha^{-1} in each of the first few irrigations of the season. PAM was applied at a concentration of 10 mg L^{-1} only in the advancing furrow stream (the period of the irrigation before runoff, when water is first traversing the dry furrow). McCutchan et al. (1994) reported that application of PAM at 2.5 mg ha^{-1} substantially reduced sediment loads in agricultural fields. Increasingly, farmers have achieved successful results applying area–equivalent rates as a small powder patch directly to the soil at the water inlet to each furrow immediately before irrigation. Efficacy of the powder patch approach was verified. With on–farm cost of PAM ranging from about $7 to $13 ha^{-1}, the use of PAM to reduce erosion has been adopted on a million acres in the U.S. as of 1998 and is also rapidly gaining acceptance overseas (Sojka et al., 1998a, 1998c). The use of PAM to reduce sediment loss is receiving additional attention throughout the Western U.S. as several states begin seeking ways to bring irrigation return–flows below mandated total maximum daily loads (TMDL) for specific contaminants.

Article was submitted for review in April 2002; approved for publication by the Soil & Water Division of ASAE in October 2002.

The authors are **James A. Entry**, Environmental Microbiologist, and **Robert E. Sojka**, Soil Scientist, USDA–ARS Northwest Irrigation and Soils Research Laboratory, Kimberly, Idaho. **Corresponding author:** James A. Entry, USDA–ARS Northwest Irrigation and Soils Research Laboratory, 3793 North 3600 East, Kimberly, Idaho 83443; phone: 208–423–6553; fax: 334–423–6555; e-mail: jentry@kimberly.ars.pn.usbr.gov.

Because of the extraordinary efficacy of non–toxic high molecular–weight anionic PAMs to remove fine suspended material in flowing water, we hypothesized that PAM use would reduce the concentration of nutrients in flowing water and would reduce total and extractable nutrients removed from irrigated fields by reducing irrigation–induced erosion. We tested this hypothesis by monitoring the effect of PAM patch treatment of furrow irrigation water within an agricultural field on nutrients in the inflow and runoff and nutrients contained in sediment carried off the field.

MATERIALS AND METHODS

STUDY SITE

The study was conducted at the USDA–ARS Northwest Irrigation and Soils Research Laboratory in Kimberly, Idaho. The soil in the test area was Portneuf silt loam (coarse–silty, mixed, superactive mesic Durinodic Xeric Haplocalcid), with 10% to 21% clay, 60% to 75% silt, and organic matter of approximately 13 g kg^{-1}. The saturated paste extract electrical conductivity (EC) ranges from 0.7 to 1.3 dS m^{-1}, with exchangeable sodium percentage (ESP) of 1.4 to 1.7, pH of 7.6 to 8.0, and a $CaCO_3$ equivalent of 2% to 8%. Slope on this site was approximately 1.5%.

EXPERIMENTAL DESIGN

The experiment was arranged in a complete randomized design with three replications. Treatments for surface flow were: (1) PAM application and no PAM applied (control), (2) distance from inflow (1 and 40 m), (3) three inflow rates (7.5, 15.0, and 22.5 L min^{-1}) corresponding to three different irrigation dates (stated below), and (4) time during irrigation (0.5, 3.5, and 6.5 h after initial inflow). Treatments for sediment, infiltration, and total and extractable nutrients were: (1) PAM application and no PAM applied (control), (2) three inflow rates (7.5, 15.0, and 22.5 L min^{-1}) corresponding to three different irrigation dates (stated below), and (3) time during irrigation (0.5, 3.5, and 6.5 h after initial inflow). Field plots were considered replications. Plots were 40 m long × 4 m wide.

POLYACRYLAMIDE APPLICATION

The polyacrylamide copolymer used was a dry granular material having an approximate molecular weight of 12 to 15 mg mol^{-1} with an 18% negative charge density (provided by CYTEC Industries of Wayne, N.J., and marketed under the tradename Superfloc 836A). PAM application involved spreading of granular PAM on the surface of approximately 0.1 m^2 area of soil in the furrow, corresponding to the 0.1 m of furrow below inflow spigots. Application amounts were 35 g of material (approximately 28 g of active ingredient). PAM was applied to the soil in a patch immediately prior to each irrigation following Natural Resource Conservation Service (NRCS) 2001 guidelines (Sojka et al., 1998a).

WATER APPLICATION

Water was applied as furrow irrigation from a storage pond, via spigoted plastic pipe, to a conventionally tilled field that was disk plowed to 10 cm depth in autumn and spring, and then roller harrowed following application of fertilizer and herbicides prior to planting. Furrows, 40 m in length, were approximately 10 cm deep, and prepared with weighted 75° V–shaped furrow–shaping tools. Furrow spacing in this crop of edible dry beans (*Phaseolus vulgaris* L.) was 76 cm. Irrigation was on every other furrow. The first irrigation was only in the wheel–track furrows, the second irrigation was only in the non–wheel furrows, and the third irrigation was only in wheel–track furrows again. Three water flow rates were used (7.5, 15.0, and 22.5 L min^{-1}), which corresponded to the three different irrigation dates: 19 June, 2 July, and 17 July 1997). Irrigation water electrical conductivity (EC) was 0.5 dS m^{-1} with a sodium adsorption ratio (SAR) of 0.4 to 0.7.

WATER SAMPLES

Furrow flow water samples at 1 and 40 m were collected with a marked beaker from the surface to a 3 cm water depth at the inlet, at 1 m distance below the water inlet and 0.9 m below the PAM patch, and at 40 m from the water inlet near the furrow outlets (fig. 1). Water in the furrows ranged from 7 to 12 cm deep, and sampling the top 3 cm of water in the furrows did not disturb sediment. Inflow water samples were taken directly from the inflow spigot prior to water contacting the soil. Three separate water samples were taken at each sampling point at each time of sampling. Samples were collected and analyzed for NH_4^+, NO_3^-, DRP, total P, K, Ca, Mg, Fe, Mn, Cu, B, and Zn using methods described below. We took a total of 162 water samples (2 PAM treatments × 3 flow rates × 3 times during irrigation × 3 reps (plots) × 3 samples taken at each sampling point). Water samples collected for nutrient analysis were frozen at –10° C, stored for 3 months, and then analyzed as described below. Nutrients in irrigation surface water, total nutrients, and extractable nutrients exported from the field reported for each furrow and treatment are the differences between inflow and outflow concentrations (i.e., inflow concentrations were subtracted from outflow concentrations to give nutrients exported from the field).

SEDIMENT SAMPLES

Per hectare sediment loss and infiltration depth were calculated based on inflow and outflow rate measurements, sediment concentration of outflow, and spacing between irrigated furrows, following previously published protocols (Sojka et al., 1992, 1994). Water inflow and outflow rates were monitored at 0.5, 3.5, and 6.5 h after irrigation was applied at 0 m (inflow) and 40 m (outflow). One–liter outflow samples were calculated at the above stated times using Imhoff cones to determine sediment volume. Sediment concentration in water was converted to mass via regression relationships described in Sojka et al. (1992, 1994), allowing the use of sediment concentration and discharge flow rate to calculate runoff water, water infiltration, and sediment and nutrient losses. Sediment in irrigation water deposited at the end of each furrow during runoff was collected after each irrigation. Three separate 10 cm diameter cores were taken to a 5.0 cm depth into the sediment deposited at the end of each furrow. Soil samples were collected, dried at 105° C, stored at 0° C, and analyzed for nutrients as described below.

Extractable and total nutrients exported from the field were calculated based on the concentration of extractable and total nutrients in sediment multiplied by the amount of sediment eroded from the field minus the concentration of nutrients in irrigation water multiplied by the amount of

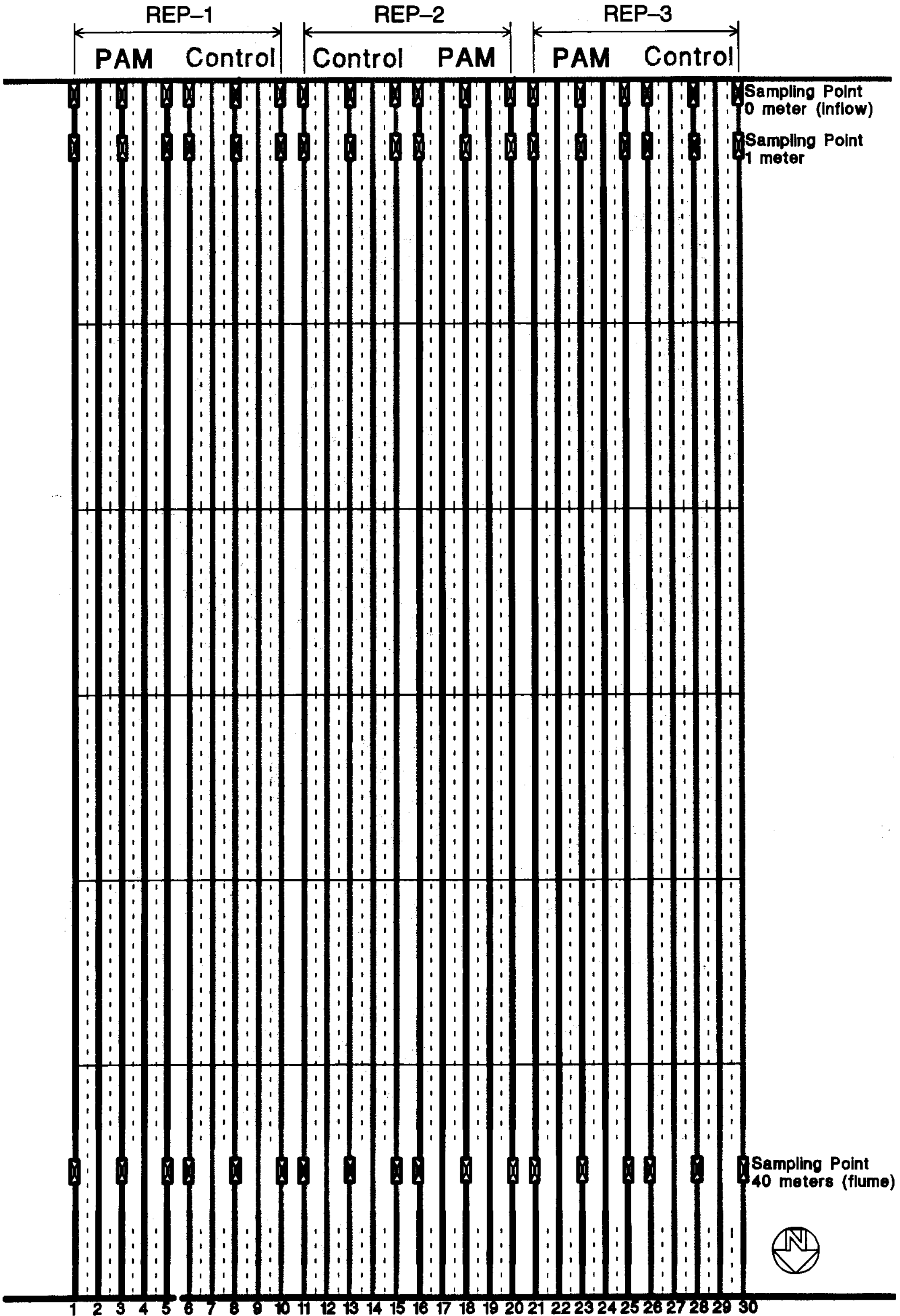

Figure 1. Plot diagram showing water and sediment sampling points. Water was sampled at 0 m (inflow), 1 m, and 40 m (outflow). Sediment was sampled at 0 m (inflow) and 40 m (outflow).

irrigation water leaving the field. We took a total of 162 sediment samples (2 PAM treatments × 3 flow rates × 3 times during irrigation × 3 reps (plots) × 3 samples taken at each sampling point).

CHEMICAL ANALYSIS

Irrigation Water

All water samples were filtered through a 0.45 μm Whatman filter. Nitrate and NH_4^+ in irrigation water were determined using the Lachat autoanalyzer (Lachat Quickchem Systems, Milwaukee, Wisc.) using methods described in Mulvaney (1996). Dissolved reactive phosphate (DRP) and total P in water were determined using methods described in Kuo (1996). Potassium, Ca, Mg, Fe, Mn, Cu, B, and Zn were determined using inductively coupled plasma emission spectrometry (ICP).

Total Nutrient Analysis of Sediment Samples

Total C was estimated by dry ashing at 525° C and assuming C equal to 50% of loss on ignition (Nelson and Sommers, 1996). Total N was determined using standard micro–Kjeldahl procedures modified for NO_3^- (Bremmner, 1996). Total concentrations of P, K, Ca, Mg, Mn, Fe, Cu, B, and Zn were determined by digestion in 98% sulfuric acid, heating at 115° C for 30 min (Hossner, 1996).

Extractable Nutrient Analysis of Sediment Samples

Phosphorus, K, Ca, Mg, Mn, Fe, Cu, B, and Zn in sediment were extracted with Mehlich III techniques (Sims, 1989). Total N, NH_4^+, and NO_3^- in water samples were determined using a Lachat autoanalyzer (Lachat Quickchem Systems, Milwaukee, Wisc.). Extractable P, K, Ca, Mg, Mn, Fe, Cu, B, and Zn were measured with an ICP.

STATISTICAL ANALYSES

All dependent variables were tested for normal distribution. Data were then analyzed using general linear models (GLM) procedures for a completely random design with Statistical Analysis Systems software (SAS, 1996). In all analyses, residuals were equally distributed with constant variances. Differences reported throughout are significant at $p \leq 0.05$, as determined by the least squares means test.

RESULTS

SEDIMENT AND INFILTRATION

Statistical comparisons of sediment and infiltration rate are presented with regard to PAM mixtures × flow rate because comparisons of sediment and infiltration rate by PAM × flow rate × sampling time were not significant at $p \leq 0.05$ (Snedecor and Cochran, 1980; Kirk, 1982). Sediment contained in inflow water was near or at zero. Mean sediment loss in the PAM and control treatments did not significantly differ at $p \leq 0.05$ when water flow was at 7.5 L min^{-1} (table 1). At 7.5 L min^{-1}, detachment and transport occurred due to the low shear forces, and most eroded soil attained deposition before reaching the end of the furrow. When water flow was at 15.0 and 22.5 L min^{-1}, sediment loss was nearly eliminated in the PAM treatment compared to the control treatment. At 15.0 and 22.5 L min^{-1} flow rates, the detachment and transport phases of the erosion process were occurring. Mean infiltration in the PAM and control treatments did not significantly differ when water flow was at 7.5 and 22.5 L min^{-1}, but infiltration was less in the PAM treatment than in the control treatment when water flow was at 15.0 L min^{-1}. Estimation of infiltration from small flumes using this method are reliable for production–sized fields of several hundred meters but are generally recognized as error prone for measurements on short furrow segments (Trout and Mackey, 1988a, 1988b). Consequently, despite the small apparent infiltration differences measured, actual treatment differences may or may not have occurred, and only the means for flow rates are meaningful as overall estimates of infiltration for the study. Most research on longer fields on these soils has typically shown about a 15% increase in the infiltration rate when PAM was applied (Sojka et al., 1998a).

Table 1. Sediment loss from an agricultural soil with and without polyacrylamide dissolved in water at different rates of flow.[a] [b]

Treatment	Flow Distance (m)	Sediment Loss (kg ha^{-1})	Infiltration (mm hr^{-1})
7.5 L min^{-1} inflow			
Control	0	0	0
Polyacrylamide	0	0	0
Control	40	85 a	43 a
Polyacrylamide	40	54 a	28 a
15.5 L min^{-1} inflow			
Control	0	0	0
Polyacrylamide	0	0	0
Control	40	5250 a	58 a
Polyacrylamide	40	163 b	42 b
22.5 L min^{-1} inflow			
Control	0	0	0
Polyacrylamide	0	0	0
Control	40	11291 a	108 a
Polyacrylamide	40	280 b	109 a

[a] Field length was 42.5 m. Top of field was sampled at 0 m from the inflow (input). Bottom of field was sampled 40 m from inflow.

[b] In each column, values followed by the same letter are not significantly different as determined by Fisher's protected least significant difference test ($P \leq 0.05$) (n = 54).

NUTRIENT CONCENTRATION IN WATER

Statistical comparisons of nutrients in filtered irrigation water are presented with regard to PAM treatment × flow rate because interactions of PAM treatment × flow rate × distance from inflow × sampling time and interactions of PAM treatment × flow rate × sampling time and PAM treatment × flow rate × distance from inflow were not significant at $p \leq 0.05$ (Snedecor and Cochran, 1980; Kirk, 1982). After irrigation water flowed 1 m, the concentrations of all nutrients in water did not differ with regard to PAM treatment or flow rate (table 2). After irrigation water flowed 40 m, NO_3^- and total P concentrations were less in furrows receiving PAM treatments than in furrows without PAM regardless of flow rate. After water flowed 1 m, export of total N, NO_3^-, total P, and K were significantly lower in irrigation water when furrows were treated with PAM than in untreated (control) furrows. After irrigation water flowed 40 m, export of total N, NO_3^-, DRP, and K were less in furrows receiving PAM treatments than in furrows without PAM regardless of flow rate (table 3).

TOTAL NUTRIENT CONCENTRATION IN SEDIMENT AND TOTAL NUTRIENTS EXPORTED VIA SEDIMENT

Statistical comparisons of total nutrients in sediment are presented with regard to PAM mixtures × flow rate because comparisons of nutrients in total nutrients by PAM × flow rate × sampling were not significant at $p \leq 0.05$ (Snedecor and Cochran, 1980; Kirk, 1982). Total nutrients exported from the field were calculated based on the concentration of total nutrients in sediment (table 4) multiplied by the amount

Table 2. Dissolved organic carbon (DOC), total nitrogen (TN), and nutrient concentration in filtered irrigation water (mg element L^{-1} water) with and without polyacrylamide (PAM) treatment in a southern Idaho field.[a] [b]

Distance (m)	Treatment	DOC	TN	NO_3	NH_4	DRP	K	Ca	Mg	Mn	Fe	Cu	B	Zn
1	Control	0.427 a	0.360 a	0.123 a	0.006 a	0.121 b	0.434 b	3.98 a	1.260 a	0.001 a	0.010 a	0.001 a	0.006 a	0.001 a
1	PAM	0.284 a	0.889 a	0.217 a	0.098 a	0.156 b	0.390 b	3.85 a	1.214 a	0.001 a	0.010 a	0.001 a	0.005 a	0.005 a
40	Control	0.478 a	0.158 b	0.151 a	0.014 a	0.219 a	0.926 a	4.01 a	1.18a	0.001 a	0.010 a	0.001 a	0.005 a	0.005 a
40	PAM	0.506 a	0.090 c	0.020 b	0.021 a	0.017 c	0.456 b	3.89 a	1.18a	0.001 a	0.010 a	0.001 a	0.005 a	0.005 a

[a] In each column, values followed by the same letter are not significantly different as determined by the least square means test ($p \leq 0.05$; n = 54).

[b] Statistical comparisons of nutrients in filtered irrigation water are presented with regard to PAM treatment × flow rate because interactions of PAM treatment × flow rate × distance from inflow × sampling time and interactions of PAM treatment × flow rate × sampling time and PAM treatment × flow rate × distance from inflow were not significant in the GLM model ($p \leq 0.05$; n = 54).

Table 3. Dissolved organic carbon (DOC), total nitrogen (TN), and nutrient export in furrow filtered irrigation water (mg nutrient ha^{-1}) with and without polyacrylamide in a southern Idaho field.[a] [b]

Distance from Inflow (m)	Treatment	Irrigation Flow Rate (L min^{-1})	C	TN	NO_3^-	NH_4^+	DRP	K	Ca	Mg	Mn	Fe	Cu
1	Control	7.5	30.6 d	100.9 c	3.3 d	0.9 d	14.0 c	59 c	256 ba	75 d	0.06 c	0.64 c	0.06 c
1	Control	15.0	62.2 b	205.1 b	6.7 b	1.8 c	28.4 b	120 b	521 b	153 b	0.13 b	1.30 b	0.13 b
1	Control	22.5	112.9 a	372.3 a	12.2 a	3.3 ab	51.7 a	219 a	946 a	279 a	0.23 a	2.36 a	0.24 a
1	PAM	7.5	32.3 d	5.7 de	1.0 f	1.3 d	1.1 de	29 d	249 c	75 d	0.06 c	0.64 c	0.06 c
1	PAM	15.0	65.7 b	11.7 d	2.1 cf	2.7 b	2.2 d	59 c	506 b	153 b	0.13 b	1.30 b	0.13 b
1	PAM	22.5	119.4 a	21.24 d	3.9 c	4.8 a	4.1 d	107 b	918 a	275 a	0.24 a	2.63 a	0.24 a
40	Control	7.5	10.0 c	33.1 d	1.0 f	0.3 e	4.6 bd	19 d	84 d	24 e	0.02 d	0.21 d	0.02 d
40	Control	15.0	42.6 c	140.1 bc	4.6 cd	1.3 cd	19.5 bc	82 bc	356 bc	105 c	0.090 c	0.89 c	0.09 b
40	Control	22.5	61.2 b	201.9 b	6.6 b	1.8 c	28.4 b	118 b	513 b	151 bc	0.13 b	1.28 b	0.13 b
40	PAM	7.5	10.2 e	1.9 e	0.3 f	0.4 e	0.4 e	10 e	81 d	24 e	0.02 d	0.21 d	0.02 d
40	PAM	15.0	45.0 c	8.0 d	1.0 ef	1.8 c	1.6 d	40 c	346 bc	105 c	0.09 c	0.89 c	0.09 b
40	PAM	22.5	64.7 b	11.5 d	2.1 e	2.6 b	2.2 d	58 c	498 b	151 b	0.13 b	1.28 b	0.13 b

[a] In each column, values followed by the same letter are not significantly different as determined by the least square means test ($p \leq 0.05$; n = 54).

[b] Statistical comparisons of nutrients in filtered irrigation water are presented with regard to PAM treatment × flow rate because interactions of PAM treatment × flow rate × distance from inflow × sampling time and interactions of PAM treatment × flow rate × sampling time and PAM treatment × flow rate × distance from inflow were not significant in the GLM model ($p \leq 0.05$; n = 54).

Table 4. Total nutrient concentration in sediment (mg element kg^{-1} sediment) transported by irrigation water in a southern Idaho field.[a]

C	N	P	K	Ca	Mg	Mn	Fe	Cu	B	Zn
60	16	911	5140	24962	8919	591	21	19	194	86

[a] Statistical comparisons of nutrients in filtered irrigation water are presented with regard to PAM treatment × flow rate because interactions of PAM treatment × flow rate × sampling time interactions were not significant in the GLM model ($p \leq 0.05$; n = 54).

of sediment eroded from the field minus the concentration of nutrients in irrigation water multiplied by the amount of irrigation water leaving the field. Nearly all total nutrients exported via sediment carried by irrigation water increased as the flow rate increased from 7.5 to 22.5 L min^{-1} (table 5.). Export of all total nutrients in sediment carried by irrigation water was lower when furrows were treated with PAM compared to the untreated (control) furrows.

Extractable Nutrient Concentration in Sediment and Extractable Nutrients Exported via Sediment

Statistical comparisons of Mehlich III extractable nutrients in sediment are presented with regard to PAM mixtures × flow rate because comparisons of nutrients in Mehlich III extractable nutrients by PAM × flow rate × sampling were not significant at $p \leq 0.05$ (Snedecor and Cochran, 1980; Kirk, 1982). Mehlich III extractable nutrients

Table 5. Total elements exported via sediment in furrow irrigation water (mg nutrient ha^{-1}) with and without polyacrylamide treatment at 40 m from inflow eroding from a southern Idaho field.[a] [b]

Treatment	Irrigation Flow Rate (L/min)	Sediment Loss (kg ha^{-1})	Infiltration (mm hr^{-1})	C	N	P	K	Ca	Mg	Mn	Fe	Cu	B	Zn
Control	7.5	85 e	43 a	1196 e	513 d	77 d	436 d	2106 d	758 e	50 d	1784 d	1.59 c	1.64 c	7 d
Control	15.0	5250 b	58 a	82211 b	32046 b	4784 b	26985 b	131055 b	46822 b	3087 b	109944 b	9877 b	10170b	450 b
Control	22.5	11291 a	108 a	176299 a	66909 a	10291 a	58954 a	288129 a	100698 a	6641 a	236692 a	21228 a	2187.11 a	970 a
PAM	7.5	54 e	28 a	846 e	326 d	49 d	277 d	1346 d	477 e	32 d	1132 d	1.02 c	1.23 c	5 d
PAM	15.0	163 d	42 a	2493 d	984 c	148 c	837 cd	4068 c	1453 d	96 cd	3423 dc	2.97 c	3.15 c	14 d
PAM	22.5	280 c	109 a	4384 c	1671 c	256 c	1439 c	6989 c	2508 c	166 c	5989 c	5.26 c	5.41 c	24 c

[a] In each column, values followed by the same letter are not significantly different as determined by the least square means test ($p \leq 0.05$; n =54).

[b] Statistical comparisons of nutrients in filtered irrigation water are presented with regard to PAM treatment × flow rate because interactions of PAM treatment × flow rate × sampling time interactions were not significant in the GLM model ($p \leq 0.05$; n = 54).

Table 6. Mehlich III extractable nutrient concentration in sediment (mg nutrient kg^{-1} sediment) in furrow irrigation water in a southern Idaho field.[a]

P	K	Ca	Mg	Mn	Fe	Cu	B	Zn
7.1	29.3	177.0	27.2	0.2	1.3	0.7	0.3	0.4

[a] Statistical comparisons of nutrients in filtered irrigation water are presented with regard to PAM treatment × flow rate because interactions of PAM treatment × flow rate × sampling time interactions were not significant in the GLM model ($p \leq 0.05$; n = 54).

exported from the field were calculated based on the concentration of extractable nutrients in sediment (table 6) multiplied by the amount of sediment eroded from the field minus the concentration of nutrients in irrigation water multiplied by the amount of irrigation water leaving the field. Export of all Mehlich III extractable nutrients tested increased as the flow rate of irrigation water increased (table 7). Export of all Mehlich III extractable nutrients tested in sediment was lower in irrigation water when furrows were treated with PAM (table 6). By reducing the concentration of sediment carried off of a field, PAM also reduces the concentration and amount of nutrients carried off of the field because many nutrients are bound to or contained in sediment particles.

DISCUSSION

SEDIMENT LOSS AND INFILTRATION

Results of our study parallel the findings of the larger body of PAM literature for use of PAM to control irrigation–induced erosion with regard to erosion and sediment loss prevention.

Beyond the erosion prevention apparent from the data presented in the table 1, there was also a dramatic visual treatment effect. Water running off of the control furrows was turbid and sediment–laden in all cases, and furrow bottoms, following each irrigation, showed the effects of erosional scouring and sediment transport and redeposition. Within a half–hour of irrigation initiation, water in untreated control furrows was clouded with sediment, while water in PAM–treated furrows was completely clear.

NUTRIENT EXPORT FROM FIELD

Reducing organic carbon (C) in return flows reduces potential for harmful O_2 depletion in surface waters, which can drastically alter the function of aquatic ecosystems. Low O_2 resulting from metabolism of C contributes to fluvial and marine hypoxia, which can harm aquatic flora and fauna. Where surface water is used as a source of drinking water, expensive treatment is necessary to remove dissolved organic carbon in order to prevent trihalomethane formation during chlorination for the removal of harmful microorganisms. Elevated concentrations of nutrients and C in water may enhance the survival of some microorganisms that are potentially harmful to humans (Moe, 1997; Roszak and Colwell, 1987).

Extractable nutrient concentrations in sediment eroded from fields are similar to those reported in loam soils in southern Idaho (Westermann et al., 1994a, 1994b). However, accumulated sediment and total nutrient losses have not been previously reported for loam soils in southern Idaho. The prevention of soil particle transport from fields to water sources should help keep nutrients in the soil and out of surface waters, where sediment and additional N and P contribute to algal blooms and changes in aquatic flora and fauna.

PAM may remove nutrients in water that are disassociated from soil particles either by preventing them from being suspended and dissolved or desorbed into solution as water contacts soil particles and/or by sorbing free ions in solution to PAM itself or to soil particles that flocculate and settle out of irrigation water (Orts et al., 2000). Coulombic and Van der Waals forces attract soil particles to PAM (Orts et al., 2000). These surface attractions stabilize the soil structure by enhancing particle cohesion, thus increasing resistance to shear–induced detachment and preventing transport of soil particles and ions in runoff. The few particles that detach are quickly flocculated by PAM.

Calcium electrolytes are needed in irrigation water when using anionic PAM for infiltration and erosion control. Modest amounts of Ca^{2+} shrink the electrical double layer surrounding soil particles and bridge the anionic surfaces of soil particles and PAM molecules, enabling flocculation (Orts et al., 2001; Wallace and Wallace, 1996). Calcium ions act as a bridge between anionic soil surfaces and the anionic PAM macromolecule. Calcium has a double charge and small hydrated radius, which favors flocculation. By contrast, sodium ions have a large hydrated radius, which impairs ion bridging, generally leading to dispersion rather than flocculation of solids. The anionic charges on PAM may sorb positively charged nutrients in either soils or water. We hypothesized that when PAM reacts with Al^{3+} and Ca^{2+} in soils or water, the cations bind with anionic nutrients such as ortho–P and NO_3^-. Free Al^{+3} and Ca^{2+} most likely bind with anionic sites on the PAM molecule, forming a bridge with

Table 7. Export of Mehlich III extractable nutrients in sediment from furrow irrigation water (mg element ha^{-1} land) flowing off of a southern Idaho field with and without polyacrylamide treatment.[a] [b]

Treatment	Irrigation Flow Rate (L/min)	P	K	Ca	Mg	Mn	Fe	Cu	B	Zn
Control	7.5	607 e	2492 e	15059 e	3080 e	193 c	139 e	56 e	24 e	33 e
Control	15.0	38417 b	153940 a	929737 b	142681 b	1197 b	8591 b	2092 b	1486 b	2065 b
Control	22.5	80695 a	331123 b	1999544 a	366759 a	2576 a	14835 a	4490 a	3225 a	4441 a
PAM	7.5	385 f	1582 e	9563 f	1467 f	12 e	88 f	22 f	15 f	21 f
PAM	15.0	1164 d	4779 d	28943 d	4428 d	37 de	267 d	107 d	46 d	64 d
PAM	22.5	2000 c	8211 c	49587 c	7625 c	63 d	421 c	185 c	79 c	110 c

[a] In each column, values followed by the same letter are not significantly different as determined by the least square means test ($p \leq 0.05$; n = 54).

[b] Statistical comparisons of nutrients in filtered irrigation water are presented with regard to PAM treatment × flow rate because interactions of PAM treatment × flow rate × sampling time interactions were not significant in the GLM model ($p \leq 0.05$; n = 54).

anionic nutrients such as DRP and NO_3^-. Further investigation to determine the efficacy of PAM to remove nutrients from water should include acidic soils. Using PAM to remove nutrients from wastewater may produce different results in acidic soils, especially when considering binding properties in DRP and total P.

Polyacrylamide reduced the amount of total and extractable micronutrients exported off of the field because the treatment reduced sediment loss. Micronutrients are essential to plant growth and yield. Iron and Zn are often unavailable to crops grown in Idaho due to the high pH soils. Soils are not always analyzed for micronutrient concentrations prior to planting, and therefore deficiencies are sometimes not detected until well into the growing season. Treatment with PAM may save producers lost revenue by not only preventing the loss of soil N and P, which is usually measured and if deficient can be corrected, but also by preventing the loss of micronutrients.

ENVIRONMENTAL CONSIDERATIONS

Environmental and safety considerations of anionic PAMs have been reviewed (Barvenik, 1994; Bologna et al., 1999; Seybold, 1994). The most significant environmental effect of PAM use is its erosion reduction, protecting surface waters from sediment and other contaminants washed from eroding fields. PAM greatly reduces nutrients, pesticides, and biological oxygen demand of irrigation return flows (Agassi et al., 1995; Lentz et al., 1998, 2001). In Australian tests of PAM, sediment, nutrient, and pesticide reductions exceeded levels achieved by traditional conservation farming methods (Waters et al., 1999). There are some specific environmental issues related to PAM charge type and purity. Used at prescribed rates, anionic PAMs are environmentally safe. Cationic and neutral PAMs have toxicities warranting caution or preclusion from sensitive environmental uses. The USDA Natural Resource Conservation Service (NRCS) specifies anionic PAMs for controlling irrigation–induced erosion. Negative impacts have not been documented for aquatic macrofauna, microorganisms, or crop species for the anionic PAMs used for erosion control when applied at recommended concentrations and rates (Kay–Shoemake et al., 1998a, 1998b, 2000).

SEDIMENT AND NUTRIENT LOSS

In furrow–irrigated fields, PAM mixed at 10 mg PAM per liter of water in the advance phase of the irrigations reduced dissolved reactive P losses by 86%, and PAM that was continuously dissolved in water at 1 mg PAM per liter of water reduced dissolved reactive P losses by 77% (Lentz at al., 1996). In a similar study, in furrow–irrigated fields, PAM mixed at 10 mg PAM per liter of water in the advance phase of the irrigations reduced total P losses by 92% and dissolved reactive P losses by 87% relative to controls (Lentz et al., 2001). These reductions were accomplished not only because PAM lowered concentrations of total and dissolved reactive P in runoff water, but also because PAM decreased the volume of furrow runoff water (Lentz et al., 2001). A subsequent percolation study showed that PAM mixed at 10 mg PAM per liter of water in the first 30 min of the irrigations did not result in an increase in field–wide losses of water–soluble nutrients (Lentz et al., 2001). Entry and Sojka (2000) also found that animal wastewater that flowed over PAM at 7.5 and 15.5 L min^{-1} reduced total P by 70% and dissolved reactive P by 50%. Our results agreed with those of Lentz et al. (1996) and Lentz et al. (2001). We found that after irrigation water flowed 40 m, export of total N, NO_3^-, total P, and K were less in furrows receiving PAM treatments than in furrows without PAM. We also found that PAM reduced the amount of total and extractable nutrients exported off of the field because the treatment reduced both nutrients dissolved in irrigation water and nutrients contained in sediment.

The water–soluble anionic PAMs used in this study are recommended for use in erosion control. They are very large anionic molecules that have been shown to be safe for a variety of food, pharmaceutical, and sensitive environmental applications (Barvenik, 1994). They should not be confused with gel–forming cross–linked PAM or evaluated with other PAM formulations, especially cationic PAMs, which have known safety concerns related to their specific chemistries (Barvenik, 1994). Environmental regulation, safety, and toxicity issues related to PAM use have been extensively reviewed (Barvenik, 1994; Seybold, 1994; Sojka and Surpaneni, 2000).

Potential benefits of PAM to reduce nutrient flow to surface water are: (1) it is inexpensive, (2) it can be quickly spread on the soil surface prior to irrigation, and (3) it can be used along with other techniques and management strategies to reduce the input of sediment and nutrients to water resources. Cost analysis and testing of PAM use in various agricultural operations is necessary, but our research demonstrates the potential of PAM as a valuable tool to allow farm operations to control nutrient loss from their operations. Agricultural operators should not expect the development of PAM products or new technologies to preclude the need for a variety of best management practices or common sense. Best results of new pollution mitigation technologies will most likely be achieved by using them with best management practices and sound animal management practices, but also having PAM as an additional tool for use in appropriate situations.

REFERENCES

Agassi, M., J. Letey, W. J. Farmer, and P. Clark. 1995. Soil erosion contribution to pesticide transport by furrow irrigation. *J. Environ. Qual.* 24(5): 892–895.

Barvenik, F. W. 1994. Polyacrylamide characteristics related to soil applications. *Soil Sci.* 158(4): 235–243.

Bjorneberg, D. L., D. L. Karlan, R. S. Kanwar, and C. A. Cambardella. 1998. Alternative N fertilizer management strategies effects on subsurface drain effluent and N uptake. *Applied Eng. in Agric.* 14(5): 469–473.

Bologna, L. S., F. F. Andrawes, F. W. Barvenik, R. D. Lentz, and R. E. Sojka. 1999. Analysis of residual acrylamide in field crops. *J. Chromat. Sci.* 37(1): 240–244.

Bremmner, H. M. 1996. Nitrogen–total. In *Methods of Soil Analysis: Part 3. Chemical Methods*, 1085–1122. D. L. Sparks, ed. Madison, Wisc.: ASA.

Brown, M. J., D. L. Carter, and J. A. Bondurant. 1974. Sediment in irrigation and drainage waters and sediment inputs and outputs for two large tracts in southern Idaho. *J. Environ. Qual.* 3(1): 347–351.

Carter, D. L., M. J. Brown, C. W. Robbins, and J. A. Bondurant. 1974. Phosphorus associated with sediments in irrigation and drainage waters for two large tracts in southern Idaho. *J. Environ. Qual.* 3(1): 287–291.

Cooper, S. R., and G. S. Brush. 1993. A 2,500–year history of anoxia and eutrophication in Chesapeake Bay. *Estuaries* 16(2): 617–626.

David, M. B., and L. E. Gentry. 2000. Anthropogenic inputs of nitrogen and phosphorus and riverine export for Illinois, USA. *J. Environ. Qual.* 29(2): 494–508.

Davis, S. M. 1991. Growth, decomposition, and nutrient retention of *Cladium jamaicense* Cranz. and *Typha domingenis* Pers. in the Florida Everglades. *Aquat. Bot.* 40(1): 203–224.

Edwards, A. C., H. Twist, and G. A. Codd. 2000. Assessing the impact of terrestrially derived phosphorus on flowing water systems. *J. Environ. Qual.* 29(1): 117–124.

Entry, J. A., and R. E. Sojka. 2000. The efficacy of polyacrylamide–related compounds to remove microorganisms and nutrients from animal wastewater. *J. Environ. Qual.* 29(6): 1905–1914.

Entry, J. A., I. Phillips, H. Stratton, and R. E. Sojka. 2002. Efficacy of polyacrylamide+$Al(SO_4)_3$ and polyacrylamide+CaO to filter microorganisms and nutrients from animal wastewater. *Environmental Pollution*. 121(3): 453–462.

Hossner, L. 1996. Dissolution for total elements. In *Methods of Soil Analysis: Part 3. Chemical Methods*, 49–64. D. L. Sparks, ed. Madison, Wisc.: ASA.

Kay–Shoemake, J. L., M. E. Watwood, R. D. Lentz, and R. E. Sojka. 1998a. Polyacrylamide as an organic nitrogen source for soil microorganisms with potential impact on inorganic soil nitrogen in agricultural soil. *Soil Biol. Biochem.* 30(13): 1045–1052.

Kay–Shoemake, J. L., M. E. Watwood, R. E. Sojka, and R. D Lentz. 1998b. Polyacrylamide as a substrate for microbial amidase. *Soil Biol. Biochem.* 30(13): 1647–1654.

Kay–Shoemake, J. L., M. E. Watwood, R. E Sojka, and R. D. Lentz. 2000. Soil amidase activity in polyacrylamide (PAM) treated soils and potential activity toward common amide containing agrochemicals. *Biol. Fertil. Soils* 31(1): 183–186.

Kirk, R. E. 1982. *Experimental Design: Procedures for the Behavioral Sciences.* 2nd ed. Belmont, Cal.: Brooks Cole Publishing.

Koch, M. S., and K. R. Reddy. 1992. Distribution of soil and plant nutrients along a trophic gradient in the Florida Everglades. *Soil. Sci. Soc. Am. J.* 56(5): 1492–1499.

Kuo, S., 1996. Phosporus. In *Methods of Soil Analysis: Part 3. Chemical Methods*, 869–920. D. L. Sparks, ed. Madison, Wisc.: ASA.

Lentz, R. D., and R. E. Sojka. 1994. Field results using polyacrylamide to manage furrow erosion and infiltration. *Soil Sci.* 158(4): 274–282.

Lentz, R. D., I. Shainberg, R. E. Sojka, and D. L. Carter. 1992. Preventing irrigation furrow erosion with small applications of polymers. *Soil Sci. Soc. Am. J.* 56(6): 1926–1932.

Lentz, R. D., R. E. Sojka, and J. A. Forester. 1996. Estimating polyacrylamide concentration in irrigation water. *J. Environ. Qual.* 25(6): 1015–1024.

Lentz, R. D., R. E. Sojka, and C. W. Robbins. 1998. Reducing phosphorus losses from surface–irrigated fields: Emerging polyacrylamide technology. *J. Environ. Qual.* 27(2): 305–312.

Lentz, R. D., R. E. Sojka, and C. W. Ross. 2000. Polymer charge and molecular weight effects on treated irrigation furrow processes. *Int. J. Sed. Res.* 1(1): 17–30.

Lentz, R. D., R. E. Sojka, C. W. Robbins, D. C. Kincaid, and D. T. Westermann. 2001. Polyacrylamide for surface irrigation to increase nutrient–use efficiency and protect water quality. *Comm. Soil Sci. Plant Anal.* 32(7): 1203–1220.

McCutchan, H., P. Osterli, and J. Letey. 1994. Polymers check furrow erosion, help river life. *Calif. Agric.* 47(1): 10–11.

Moe, C. L. 1997. Waterborne transmission of infectious agents. In *Manual of Environmental Microbiology*, 136–152. C. J. Hurst, G. R. Knudsen, M. J. McInerney, L. D. Stetzenbach, and M. V. Walter, eds. Washington. D.C.: American Society of Microbiology Press.

Mulvaney, R. L. 1996. Nitrogen inorganic forms. In *Methods of Soil Analysis: Part 2. Chemical and Microbiological Properties*, 1123–1184. D. L. Sparks, ed. Madison, Wisc.: ASA.

Nelson, D. W., and L. E. Sommers. 1996. Total carbon, organic carbon, and organic matter. In *Methods of Soil Analysis: Part 3. Chemical Methods*, 961–1010. D. L. Sparks, ed. Madison, Wisc.: ASA.

Orts, W. J., R. E. Sojka, and G. M. Glenn. 2000. Biopolymer additives to reduce soil erosion–induced soil losses during irrigation. *Industrial Crops and Products* 11(1): 19–29.

Orts, W. J., R. E. Sojka, G. M. Glenn, and R. A. Gross. 2001. Biopolymer additives for the reduction of soil erosion losses during irrigation. In *Biopolymers from Polysaccharides and Agroproteins*, 102–116. R. A. Gross and C. Scholz, eds. ACS Series 786. Washington, D.C. American Chemical Society.

Roszak, D. B., and R. R. Colwell. 1987. Survival strategies of bacteria in the natural environment. *Microbiol. Rev.* 51(1): 365–379.

SAS. 1996. *SAS User's Guide: Statistics.* Version 6.03 edition. Cary, N.C.: SAS Institute, Inc.

Seybold, C. A. 1994. Polyacrylamide review: Soil conditioning and environmental fate. *Comm. Soil Sci. Plant Anal.* 25(11): 2171–2185.

Sharpley, A., B. Foy, and P. Withers. 2000. Practical and innovative measures for the control of agricultural phosphorus losses to water: An overview. *J. Environ. Qual.* 29(1): 1–9.

Sims, J. T. 1989. Comparison of Mehlich 1 and Mehlich 3 techniques for extractants for P, K, Ca, Mg, Mn, Cu, and Zn in Atlantic coastal soils. *Comm. Soil Sci. Plant Anal.* 20(17): 1707–1726.

Snedecor, W. G., and W. G. Cochran. 1980. *Statistical Methods.* 7th ed. Ames, Iowa: Iowa State University Press.

Sojka, R. E. 1998. Understanding and managing irrigation–induced erosion. In *Advances in Soil and Water Conservation*, 21–37. F. J. Pierce and W. W. Frye, eds. Chelsea, Mich.: Ann Arbor Press.

Sojka, R. E., and J. A. Entry, 2000. Influence of polyacrylamide application to soil on movement of microorganisms in runoff water. *Environ. Pollut.* 108(3): 405–412.

Sojka, R. E., and A. Surpaneni. 2000. Potential use of polyacrylamide (PAM) in Australian agriculture to improve off– and on–site environmental impacts and infiltration management. Report UNE39. Tatura, Victoria, Australia: Australian Land and Water Resources.

Sojka, R. E., M. J. Brown, and D. L. Carter. 1992. Imhoff cone determination of sediment in irrigation runoff. *Soil Sci. Soc. Am. J.* 56(3): 884–890.

Sojka, R. E., R. D. Lentz, and J. A. Foerster. 1994. Software utilizing Imhoff cone volumes to estimate furrow–irrigation erosion. *J. Soil and Water Conser.* 49(4): 400–406.

Sojka, R. E., R. D. Lentz, C. W. Ross, T. J. Trout, D. L. Bjorneberg, and J. K. Aase. 1998a. Polyacrylamide effects on infiltration in irrigated agriculture. *J. Soil. Water. Cons.* 54(4): 325–331.

Sojka, R. E., R. D. Lentz, and D. T. Westermann. 1998b. Water and erosion management with multiple applications of polyacrylamide in furrow irrigation. *Soil Sci. Soc. Am. J.* 62(6): 1672–1680.

Sojka, R. E., R. D. Lentz, D. L. Bjorneberg, and J. K. Aase. 1998c. The PAMphlet: A concise guide for safe and practical use of polyacrylamide (PAM) for irrigation–induced erosioncontrol and infiltration enhancement. Report 98–02. Kimberley, Idaho: USDA–ARS Northwest Irrigation and Soils Research Laboratory.

Stevenson, J. C., L. W. Staver, and K. W. Staver. 1993. Water quality associated with survival of submersed aquatic vegetation along an estuarine gradient. *Estuaries* 16(2): 346–361.

Trout, T. J., and B. E. Mackey. 1988a. Inflow–outflow infiltration measurement accuracy. *J. Irrig. Drain. Eng.* 114(2): 256–265.

_____. 1988b. Furrow flow measurement accuracy. *J. Irrig. Drain. Eng.* 114(2): 244–255.

Trout, T. J., and W. H. Neibling. 1993. Erosion and sedimentation processes on irrigated fields. *J. Irrig. Drain. Eng.* 119(6): 929–946.

Wallace, A., and G. A. Wallace. 1996. Need for solution or exchangeable calcium and/or critical EC level for flocculation of clay by polyacrylamides. In *Managing Irrigation–Induced Erosion and Infiltration with Polyacrylamide*, 59–63. R. E. Sojka and R. D. Lentz, eds. Misc. Publ. No. 101–96. Twin Falls, Idaho: University of Idaho.

Waters, D., R. Drysdale, and S. Kimber. 1999. Benefits of planting into wheat stubble. *The Australian Cotton Grower Magazine* 20(1): 8–13.

Westermann, D. T., D. W. James, T. A. Tindall, and R. L. Hurst. 1994a. Nitrogen and potassium fertilization of potatoes: Sugars and starch. *Am. Potato. J.* 71(3): 433–453.

Westermann, D. T., S. M. Bosma, and M. A. Kay. 1994b. Nutrient concentration relationships between the fourth petiole and upper–stem of potato plants. *Am. Potato. J.* 71(3): 817–828.