Long-Term Polyacrylamide Formulation Effects on Soil Erosion, Water Infiltration, and Yields of Furrow-Irrigated Crops

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Irrigation

ABSTRACT

Two formulations of water-soluble anionic polyacrylamide (WSPAM) are used in agriculture to reduce erosion and manage infiltration in furrow irrigations, although few if any reports have compared their effectiveness. A control and two WSPAMs, a granular form and the inverse emulsion, or oil-based liquid form, were applied to irrigation water supplied to furrows formed in a silt loam soil with 1.5% slope during each irrigation from 1993 to 1999. Stock solutions prepared from the two WSPAMs in tap water were injected into furrow inflows to attain a concentration of 10 mg L^{-1} only during furrow advance. During irrigations, furrow inflow and runoff rates, and runoff sediment concentrations were measured. Crop yields were measured in five of the 7 yr. Relative to controls, both WSPAM treatments reduced runoff sediment loss equally well, decreasing soil losses by 84% per irrigation, and prevented the loss of 47.8 Mg soil ha^{-1} over the 7-yr period. The yearly soil loss reductions produced by WSPAMs ranged from 66 to 99%, and may reflect changes in the electrical conductivity (EC) of the irrigation water. Both WSPAM treatments increased the proportion of applied irrigation water that infiltrated into newly formed furrows, but the emulsion produced the greatest overall increase in water infiltration fraction. As a class, WSPAM treatments increased yields by 14.3% for bean ('Viva Pink' *Phaseolus vulgaris* L.) and 4.5% for silage corn (*Zea mays* L.), suggesting that the cost of WSPAM applications may be recoverable. While the two WSPAM formulations provide equivalent erosion protection, differences in infiltration effects, product costs, and potential environmental impacts should be considered when selecting the formulation.

Applying organic polymers such as WSPAM to soil stabilizes its structure and increases its resistance to erosion (Nadler and Letey, 1989). Researchers have utilized this capability in agriculture in an effort to increase infiltration and reduce erosion associated with rainfall and irrigation. While much research has focused on rainfall and/or sprinkler applications (Sojka et al., 2007; Abu-Zreig et al., 2007; Petersen et al., 2007), this report is concerned with surface irrigation applications.

Terry and Nelson (1986) applied aqueous WSPAM solution to the entire soil surface (200 kg ha^{-1}) of flood irrigated plots to decrease soil penetrometer resistance and increase infiltration. Other scientists showed that pretreating only the wetted perimeters of irrigation furrows used as little as 7 to 45 kg polymer ha^{-1}, yet reduced irrigation induced erosion by >80% (Paganyas, 1975) and increased infiltration early in the irrigation (Mitchell, 1986). Application rates of WSPAM were further reduced by amending real-time irrigation furrow inflows with as little as 10 mg L^{-1} (1–2 kg ha^{-1}) only during water advance, which reduced runoff sediment losses in newly formed furrows 69 to 99% relative to controls (Lentz et al., 1992). This economical approach was demonstrated to be effective in further studies (Lentz and Sojka, 2000), hence the Natural Resource Conservation Service developed a conservation practice standard using WSPAM for reducing soil erosion in furrow irrigation (NRCS, 2001). The standard recommends applying 1 to 10 mg L^{-1} WSPAM product to irrigation water inflows either continually or only during the initial advance of water across the field, after which untreated water is used to finish the remainder of the irrigation.

Literature on WSPAM use in agriculture has recently been reviewed (Sojka et al., 2007). After the 1 to 2 kg ha^{-1} WSPAM application was shown to be effective for erosion and infiltration management in irrigation furrows, other researchers discovered that the approach also decreased runoff losses of nutrients, sediment-associated pesticides, and microorganisms (Agassi et al., 1995; Bahr and Steiber, 1996; Oliver and Kookana, 2006a, 2006b; Sojka et al., 2007). Subsequent field research examined the 1 to 2 kg ha^{-1} WSPAM furrow treatment concept in greater detail, and evaluated its use in relation to the following: (i) different WSPAM concentrations and durations applied in irrigation inflows (Lentz and Sojka, 2000); (ii) multiple in-season WSPAM applications (Sojka et al., 1998); (iii) WSPAM molecular weight and charge (Lentz et al., 2000); (iv) WSPAM applications on steeply sloped (>4%) furrows (Lentz et al., 2003); (v) WSPAM applied as a granular patch at the furrow head (Sojka et al., 2007), combined with polysaccharide-based amendments (Bjorneberg and Sojka, 2008), as an oil-based emulsion (Weston et al., 2009) or tablet form (Oliver and Kookana, 2006a, 2006b); and (vi) WSPAM applied to furrows integrated with other erosion control practices (Leib et al., 2005; Szögi et al., 2007).

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Abbreviations: AMD, acrylamide monomer; EC, electrical conductivity; IT, irrigation type; WSPAM, water-soluble anionic polyacrylamide.

The WSPAM research published to date included relatively short-term observations and rarely reports on agronomic impacts. For example, only a few studies continued WSPAM application and monitoring of treated furrows into a second irrigation season (Sojka et al., 1998; Leib et al., 2005; Szögi et al., 2007). We are not aware of any published studies that have directly compared use of the two major types of WSPAM products for furrow irrigation, the granular or solid form (80–95% a.i.) and the inverse emulsion or oil-based liquid form (30–50% a.i.), in which the polymer occurs in aqueous droplets stabilized by surfactants in a continuous phase of a petroleum distillate (Barvenik, 1994). The objective of this research was to compare the efficacy of granular and emulsion WSPAM applications for managing infiltration and erosion in irrigated furrows, and to determine treatment effects on crop yields over a 7-yr period of continual treatment.

MATERIALS AND METHODS

Site, Soils, and Polymer

A long-term experimental plot was established in 1993 on furrow irrigated Portneuf silt loam soils (coarse-silty, mixed superactive, mesic Durinodic Xeric Haplocalcids) with 1.5% slopes near Kimberly, Idaho, USA. The silt loam surface horizon is comprised of 100 g kg^{-1} clay, 700 g kg^{-1} silt, 10 to 13 g kg^{-1} organic matter, and 5% calcium carbonate equivalent. The soil has a cation exchange capacity of 190 mmol$_c$ kg^{-1}; saturated-paste-extract EC of 0.07 S m^{-1}; exchangeable sodium percentage of 1.5; and pH of 7.7 (H_2O saturated paste). The Snake River water used for irrigation had an average EC of 0.04 S m^{-1}, sodium adsorption ratio of 0.06, and carried little sediment (<500 mg L^{-1}).

Two formulations for WSPAM were obtained from CYTEC Industries, Water Treatment and Paper Chemicals Division (now Kemira Water Solutions, 1937 West Main Street, Stamford, CT).[1] Both were linear anionic copolymers with 15 to 20 Mg mol^{-1} molecular weight (derived from viscosity measurements). The solid form, Superfloc A110 Flocculant, is an acrylamide/sodium acrylate copolymer with 18% charge density and comprised of 80% a.i. WSPAM, 5 to 10% water, plus a salt that acts as a dissolution aid. The liquid inverse emulsion form, Superfloc A1883 Flocculant (now sold as A1883RS), is an acrylamide/acrylic acid-ammonium salt copolymer with 30% charge density and contains 30% a.i. WSPAM, and approximately 30% petroleum distillate, 30% water, and 10% emulsifiers and surfactants. Stock solutions of the A110 (2400 mg L^{-1}) and A1883 (1200 mg L^{-1}) were made up from tap water (EC = 0.09 S m^{-1}, SAR = 1.5) before the irrigation and allowed to stand overnight before use.

The experimental design was a randomized complete block with three replicates. Each experimental unit was 4 m wide by 180 m long, and was separated from adjacent plots by a 1.3-m-wide buffer strip. Three treatments were included: (i) control (no WSPAM); (ii) WSPAM applied as a solution made up from solid PAM (A110) and injected into the irrigation inflows at a concentration of 10 mg L^{-1} only during irrigation advance (while water first advances down the furrow); and (iii) WSPAM applied as a solution made up from inverse emulsion WSPAM and injected identically to that of the A110 treatment. The same treatment was applied in the same plot for each irrigation and for each year during the 7-yr study. Each plot included five planted rows (0.76-m spacing) in years when the field was planted to silage corn and seven planted rows (0.55-m spacing) in years the field was planted to bean. Every other furrow was irrigated across the field. Treatments were applied to two irrigated furrows (corn) or four irrigated furrows in each plot. The buffer strip included one untreated irrigated furrow. All irrigation furrows were wheel trafficked when formed in the field to reduce furrow infiltration variability (Yoder et al., 1996). Furrows were formed by a weighted v-shaped tool attached to the toolbar and aligned with the tractor wheels.

After corn harvest the stover (15- to 30-cm-tall stems with leaves) was moldboard plowed to the 0.25-m depth. This tillage was done either in fall or spring, otherwise the field was disked to the 0.1-m depth in fall and spring. In preparation for planting in spring, fertilizer (as recommended by soil test) and preemergence herbicide was applied to the soil and incorporated with one or two roller harrow passes. The fields were typically planted in mid-May for corn and first of June for bean with some variation as noted in Table 1. The v-shaped, 0.1-m-deep furrows were formed as an integral part of the

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

Table 1. Crop, planting, irrigation, and climate characteristics for years included in the study.

Year	Crop	Planting date	Harvest date	Irrigations	Date of 1st irrigation	Date of last irrigation	June–Sept. potential ET†	June–Sept. mean air temp.	June–Sept. precipitation	Jan.–May precipitation‡	Irrigation water inputs
							mm	°C	mm	mm	mm
1993§	corn	17 May	21 Sept.	7	26 May	18 Aug.	760	16.3	71	159	181
1994	bean	2 June	1 Sept.	5	8 June	3 Aug.	873	19.7	32	134	217
1995	bean	1 June	7 Sept.	7	15 June	16 Aug.	788	18.1	103	239	226
1996	fallow¶	–	–	2	5 Sept.	19 Sept.	879	19.0	32	154	73
1997	corn	8 July#	21 Sept.	5	16 July	10 Sept.	799	18.6	75	117	186
1998	corn	1 June#	21 Sept.	5	8 July	2 Sept.	797	19.3	76	234	239
1999	corn	18 May	28 Sept.	7	23 June	8 Sept.	890	18.4	21	170	347

† Cumulative evapotranspiration potential during the 4-mo period permits year to year comparisons. Actual crop ET was less than these potential values.

‡ Preseason precipitation amounts indicate how soil water storage potential changed from year to year.

§ Yield measurements were not determined for this crop.

¶ In 1996, soil water percolation samplers were installed below the soil surface in the field, so a crop was not grown.

In 1997, the planting date was delayed to allow completion of the aboveground soil water collection equipment. A corn hybrid with 75-d maturity was planted to match the brief season. In 1998, the planting date was delayed due to heavy spring rains.

planting operation. The row crops were cultivated one to three times during each growing season using tillage operations that simultaneously reshaped the irrigation furrows. One or two cultivation–furrow reshaping operations were done in each cropping season to control weeds. In some years, an additional cultivation–furrow reshaping operation was included to provide additional data on WSPAM effects on freshly formed furrows.

Crop yields were measured in all years except 1993 and 1996. Bean yields were determined from two 3-m lengths of row, one taken about 40 m from the inflow end of the row (upper half), and the other about 35 m from the outflow-end of the row (lower half). Standing corn (silage) yields were also measured at upper-half and lower-half field locations. At each location, two 3-m lengths of the planted corn row were collected, one from either side of a treated irrigation furrow.

IRRIGATION

A gated pipe with adjustable spigots conveyed irrigation water across the plots at the head, or inflow end, of the furrows. Irrigation outflows from each furrow entered a tail-water ditch that ran perpendicular to the furrows at the bottom of the field. At the head of each plot, a manifold made from 0.15-m-diameter PVC pipe withdrew water from the gated pipe and directed it under equal hydrostatic pressure into each of the two or four furrows that supplied the experimental unit. A 0.05-m diameter PVC pipe connected to the inflow-end of the manifold acted as a prestage mixing chamber. Incoming irrigation water was injected with WSPAM stock solution and flow turbulence occurring in the 0.05-m-diam. pipe mixed the two fluids before they entered the larger manifold chamber. During the irrigation advance-phase, a peristaltic pump injected the A110 or A1883 WSPAM stock solution into the manifold's prestage section at a rate required to attain the target concentration of 10 mg L^{-1} a.i. in the furrow irrigation stream.

Irrigation inflows and set times used before 1996 differed from that used afterward. In years 1993 to 1996, inflow rates of all furrows were 23 L min^{-1} initially, and were then reduced to 15 L min^{-1} after furrow streams had advanced to the end of the furrows. Irrigation set times were identical for all treatments, typically 12 h, except for the first two irrigations in 1994 and 1995, which were shortened to 8 h. In the seasons after 1996, control furrows were set at 15 L min^{-1}. Because WSPAM increases infiltration and slows furrow advance on freshly cultivated furrows (Sojka et al., 2007), initial irrigation inflows for WSPAM furrows were set to 45 L min^{-1}. Use of WSPAM prevented erosion that would ordinarily occur at these high inflow rates, allowed rapid furrow advancement, and increased irrigation uniformity in treated furrows. When water in treated furrows had fully advanced, inflows were decreased to 15 L min^{-1} to reduce runoff losses. During these years, treatment effects on net infiltration were monitored in real time in the plots, i.e., net infiltration for each monitored furrow was computed every 1 to 2 h as the irrigation progressed to track average treatment intake amounts (see discussion below). Using this information we adjusted irrigation set durations so that all treatments received similar net furrow infiltration amounts. Irrigation set times for post-1996 irrigations ranged from 8 to 30 h. The mean WSPAM amounts applied per irrigation in a given year ranged from 1.2 to 2.5 kg ha^{-1}, with the higher amounts used in later years when initial irrigation inflow rates for treated furrows were 45 L min^{-1}.

Furrow inflows, stream outflow rates, and sediment concentrations were measured during each monitored irrigation. Outflow rate measurements and runoff water samples were taken at 0.5-h intervals early in the irrigation, every hour during the midirrigation period, and every 3 h later in the irrigation when outflows and sediment loads had stabilized (at >7 h into the set). Inflows were measured by timing the filling rate of a known volume, and outflows were measured with long-throated v-notch flumes.

The mass of sediment per 1-L of sampled runoff was determined from the settled volume of sediment in an Imhoff cone, which was converted to a mass value via a calibration function (Lentz et al., 1992). The computer program, WASHOUT (Lentz and Sojka, 1995), fitted calibration functions for each data year and calculated net infiltration and runoff sediment losses for furrows (Lentz and Sojka, 1995). Individual calibration functions were developed for each year of irrigation, type of furrow (fresh vs. repeat), and treatment (control vs. WSPAM). WASHOUT computes the net infiltration volume for individual furrows by subtracting the total outflow volume from the total inflow volume, where inflow and outflow volumes were computed by integrating the inflow- and outflow-rate curves over time. The net infiltration depth (i.e., infiltration on an area basis) was then calculated by dividing the net infiltration volume by the field area watered by the irrigation furrow, where the watered area is the product of the spacing between irrigation furrows and the furrow length. During post-1996 irrigations, furrow inflow and runoff data were input into a modified version of the WASHOUT program, designated as WASHFIELD, which computed real-time cumulative net infiltration amounts and forecast irrigation shutoff times needed for furrow treatment groups to attain infiltration targets.

Standardized parameters for soil loss, infiltration, and crop yield were included in the analysis to permit comparisons among all years. Values for soil-loss reduction were calculated as 100 times the ratio of soil loss difference (WSPAM treatment minus average control value) to average control soil loss. The average control value was used in order that all soil loss responses could be established relative to a single, field-wide control standard in each year. Yield gain values were derived as the ratio of the WSPAM yield gain to the average control value, where yield gain was calculated as the yield difference, WSPAM minus the average control value. Again, the use of the average control yield value allowed all yields for a given year to be related to a single field-wide value. Infiltration as a fraction of irrigation inflow (infiltration fraction) was calculated as 100 times the ratio of net furrow infiltration divided by net inflow.

We assigned each irrigation to one of three irrigation types (ITs) based on the number of irrigations applied to the furrow before it was reformed: IT 1 = first irrigation on freshly formed furrows; IT 2 = second irrigation on an otherwise undisturbed furrow; and IT 3 = furrows having two or more repeat irrigations on an otherwise undisturbed furrow. All years included one or more irrigations of ITs 1, 2, or 3, except 1996, which included only two irrigations of ITs 1 and 2. Data from all

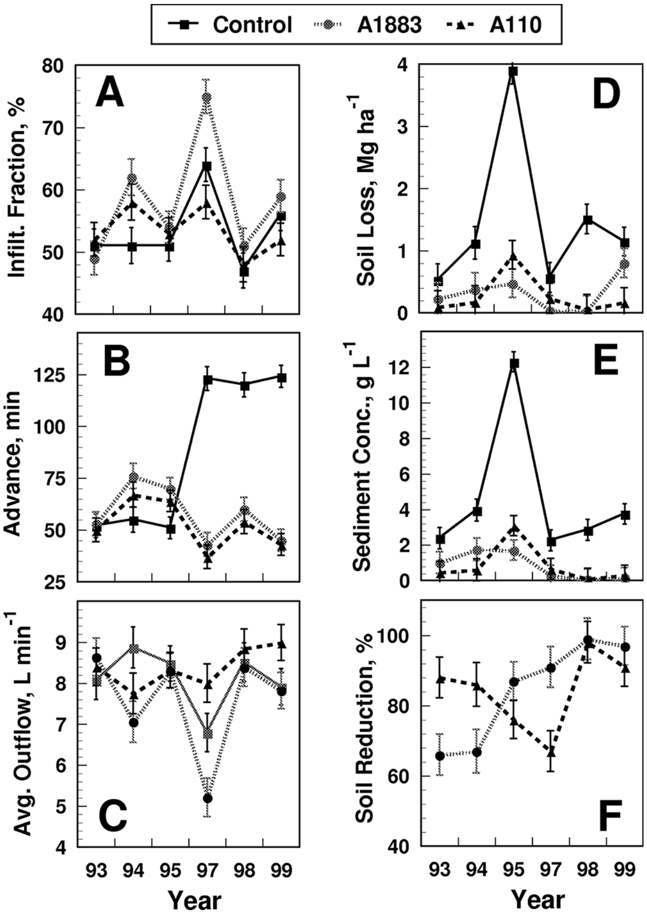

Fig. 1. Interaction effects of year and treatment on (A) infiltration fraction, (B) furrow advance period, (C) Mean furrow outflow, (D) runoff sediment loss, (E) mean runoff sediment concentration, and (F) soil loss reduction relative to controls. Values are derived from irrigation means. Each leg of an error bar equals one standard error (*n* = 9).

years except 1996 were analyzed via ANOVA, PROC Mixed (SAS Institute, 1999), using a repeated measures approach. The model included factors, treatment, year, IT, and their interactions, and accounted for correlated results between sequential irrigations. We employed a PROC Mixed model that included treatment, field location, and their interaction to evaluate crop yield, plot stand count, and yield gain on an individual crop basis. This same analysis included an orthogonal contrast to compare control vs. WSPAM treatment class effects on yield parameters. In figures presenting results from the soil loss reduction analyses (Fig. 1F, 2, 3, 4F), all control values equal zero, and to simplify graphs were not displayed. Seasonal cumulative values for net infiltration, infiltration fraction, and soil losses were determined. An ANOVA on the cumulative values was conducted to determine the effect of treatment and year on each of the irrigation parameters. The cumulative net infiltration and infiltration fraction data were divided into two sets before analysis: one set included years 1993, 1994, and 1995, years for which all furrows had the same inflow rate and irrigation length; and the other set included 1997, 1998, and 1999, years for which control furrows had lower inflow rates than WSPAM furrows, and irrigation lengths had been adjusted so that all furrows realized similar net infiltration. All analyses were conducted using a $P = 0.05$ significance level.

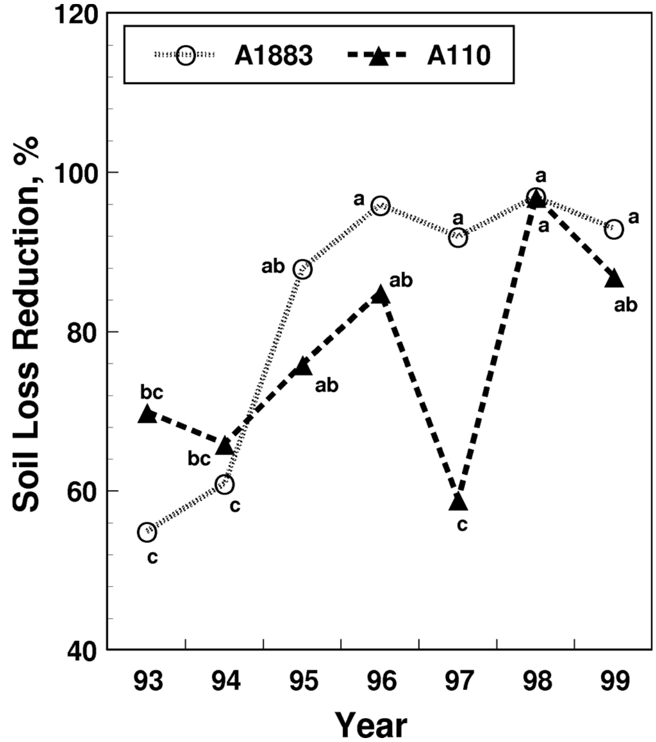

Fig. 2. The influence of inverse emulsion (A1883) and granular (A110) water-soluble anionic polyacrylamide treatments on yearly soil loss reduction (relative to controls). Values are derived from mean cumulative yearly soil losses. Quantities for symbols followed by similar letters are not significantly different at $P \leq 0.05$.

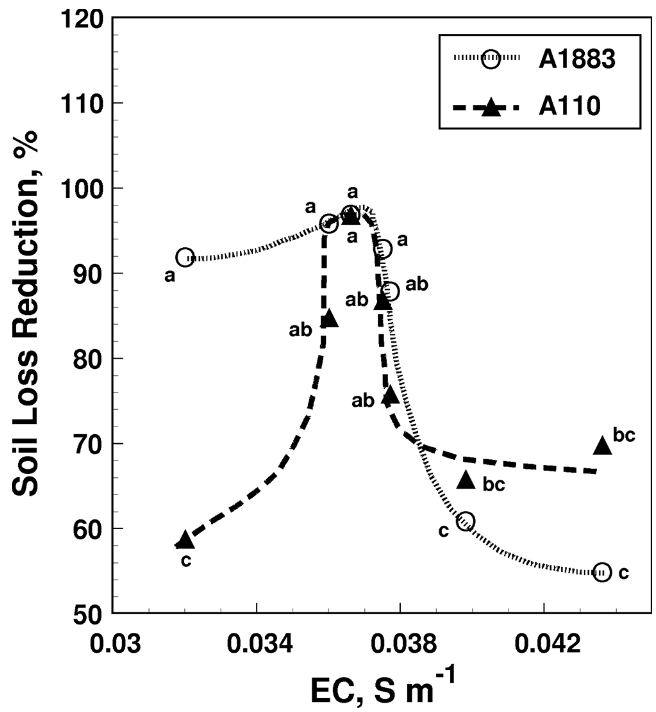

Fig. 3. The relationship between the mean electrical conductivity (EC) of supplied irrigation water and the reduction in cumulative yearly soil losses attained by inverse emulsion (A1883) and granular (A110) water-soluble anionic polyacrylamide treatments (relative to controls).

RESULTS AND DISCUSSION

The ANOVA in Table 2 examined data for individual irrigations across the six cropped seasons. Results showed that treatments significantly influenced runoff sediment concentrations and losses, soil loss reduction, mean outflow rate, furrow advance, and infiltration fraction, but not net infiltration, during irrigations. Both IT and year also significantly influenced each of these irrigation parameters, including net infiltration. Furthermore, the analysis revealed significant effects of treatment-by-IT and/or treatment-by-year interactions on all irrigation parameters.

Soil Losses and Erosion Control

The A1883 and A110 treatments reduced erosion equivalently, by 84% relative to controls in each irrigation (Table 3). Mean soil loss was an average 0.24 Mg ha^{-1} per irrigation for WSPAM treatments versus 1.46 Mg ha^{-1} for controls. Over the entire 1993-to-1999 period, WSPAM treatments prevented the loss of an average 47.8 Mg soil ha^{-1}, in comparison with soil losses in control furrows (Table 4). Mean soil losses per irrigation varied somewhat from year to year, typically ranging from 0.29 to 56 Mg ha^{-1}; however, 1995 erosion losses were significantly greater than other years, 1.77 Mg ha^{-1} (Table 3). The reason for this is not clear. Mean soil losses per year are shown for each treatment and year in Fig. 1D. These data suggest a trend in the response pattern, that is, in 1993 to 1994, mean soil losses for A110 were smaller than that of A1883, while the reverse was indicated for later years. We observed this relationship more clearly when examining the year-by-treatment interaction on soil-loss reduction (Fig. 1F). In 1997, the diminished efficacy of A110 was so striking that we suspected our WSPAM material was substandard; however, material obtained from a different batch tested similarly. A similar response pattern occurred when soil loss reduction was computed from yearly cumulative total soil loss values (Fig. 2), except that differences between years 1993 and 1994 were not significant.

When dissolved in water, the segments of the WSPAM molecular chain fold back on one another, forming a random coil configuration with characteristic diameter (Bolto and Gregory, 2007). Flocculation activity of dissolved anionic WSPAM decreases as the polymer coil diameter decreases

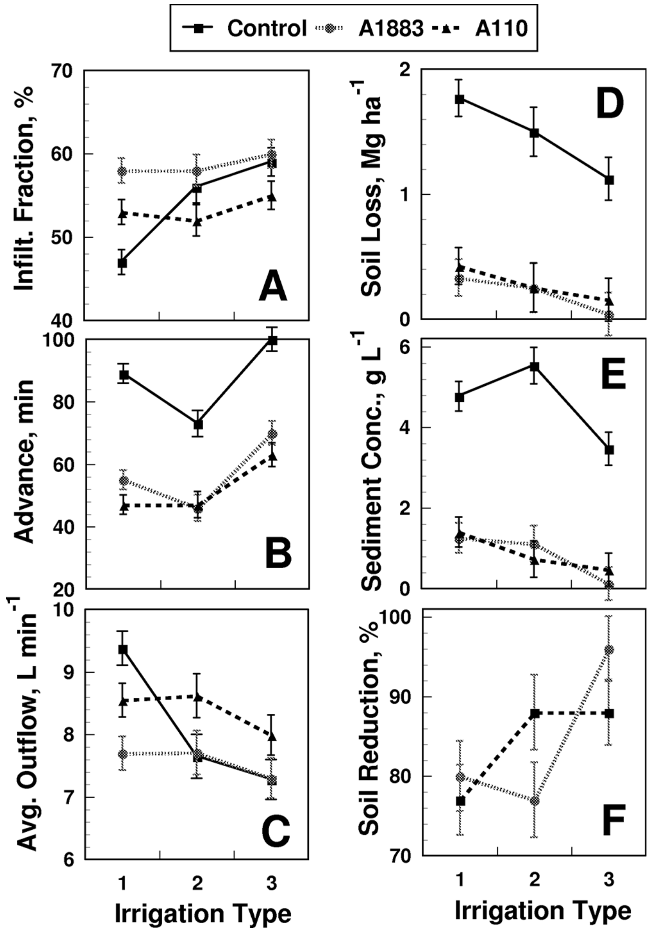

Fig. 4. The effect of treatment and irrigation-type on (A) infiltration fraction, (B) furrow advance period, (C) mean furrow outflow, (D) runoff sediment loss, (E) mean runoff sediment concentration, and (F) soil loss reduction relative to controls. Values are derived from irrigation means. Each leg of an error bar equals one standard error (*n* = 18).

(Henderson and Wheatley, 1987), and coil diameter decreases with increasing dissolved salt concentration (Lakatos et al., 1981). As the number of cations in solution increase, more are available to screen the negatively charged sites on WSPAM molecules (Van De Steeg et al., 1992), which decreases repulsive forces between coil segments and reduces the diameter of

Table 2. The influence of water-soluble anionic polyacrylamide (WSPAM) treatment, irrigation type, and year on furrow erosion and infiltration parameters. Table gives *P* values for main effect and interaction terms derived from an ANOVA.

Source of variation	Sediment loss	Sediment concentration	Soil loss reduction†	Mean outflow rate	Furrow advance	Net infiltration	Infiltration as fraction of inflow
	Dependent variable						
	P						
Treatment (TRT)	***	***	***	**	***	0.10	**
Irrigation Type (IT)	**	***	***	***	***	***	***
Year	***	***	***	**	***	***	***
TRT × IT	0.65	0.20	*	***	0.20	0.92	***
TRT × Year	***	***	***	*	***	0.91	*
IT × Year	0.88	***	0.60	***	***	***	***
TRT × IT × Year	0.99	0.34	**	0.74	0.30	0.99	0.67
Orthogonal contrast							
Control vs. WSPAMs	***	***	***	0.57	***	*	0.09

* $P \leq 0.05$.

** $P \leq 0.01$.

*** $P \leq 0.001$.

† Soil loss reduction was computed relative to controls. The soil loss reduction values for WSPAM treatments were compared with the control value, which was zero.

Table 3. Irrigation mean values for furrow runoff sediment losses, sediment concentration, sediment reduction, outflow rate, advance time, net infiltration, and infiltration fraction.

Group	Soil loss	Sediment concentration	Soil loss reduction†	Mean outflow rate	Net infiltration	Advance time	Infiltration fraction
	Mg ha^{-1}	g L^{-1}	%	L min^{-1}	mm	min	%
Treatment							
Control	1.463a‡	4.6a	0a	8.10a	36a	87a	54b
A1883	0.206b	0.83b	84b	7.57b	39a	58b	58a
A110	0.277b	0.87b	84b	8.38a	39a	53b	53b
Irrigation type							
Fresh (1)	0.842a	2.5a	78b	8.54a	39b	64b	52c
1st Repeat (2)	0.667ab	2.5a	82b	7.99b	37c	56c	55b
2+ Repeats (3)	0.438b	1.4b	92a	7.53c	46a	78a	58a
Year							
1993	0.285b	1.3b	77b	8.36a	24e	52c	51c
1994	0.559b	2.1b	76b	7.90a	42b	66b	57b
1995	1.771a	5.7a	82b	8.37a	33d	62b	53bc
1997	0.280b	1.1b	79b	6.67b	37c	68b	66a
1998	0.534b	1.0b	98a	8.58a	49a	78a	49c
1999	0.466b	1.4b	94a	8.24a	44b	71a	56b

† Soil loss reduction was computed relative to control values.

‡ If followed by the same letter, parameter values within a given column group (between rows) are not significantly different at $P \leq 0.05$.

the solvated molecule (Lakatos et al., 1981; Van De Steeg et al., 1992). We hypothesized that WSPAM efficacy for controlling erosion was related to salt concentrations in the irrigation water, which change during the irrigation season and among years, depending on the proportion of snow melt water contributed to the Snake River source. Because the WSPAM solution mixed into the irrigation water at a ratio of about 1 part stock solution to 100 parts irrigation water, and because the relaxation time of polymer molecules dissolved in water (a measure of how rapidly the dissolved molecule conformation adjusts to changes in furrow stream salt concentration) is on the order of seconds (Tam and Tiu, 1994), it seems reasonable to assume that WSPAM molecules and their activity in the furrow stream will be more influenced by the irrigation water than by the tap water used to make up the stock solution.

In Fig. 3, the yearly cumulative soil loss reductions for WSPAM treatments (from Fig. 2) were plotted as a function of the mean EC of supplied irrigation water. The erosion control efficacy for A110 peaked at a water EC of 0.0365 S m^{-1}, and declined when EC dipped below or rose above this value. The erosion control efficacy of A1883 also declined when water EC fell below 0.0365 S m^{-1}, but unlike A110, was strong at lower ECs. The data imply that an optimal water EC may exist in this soil–water system with regard to erosion control. In contrast to A110, A1883 may have retained its erosion control efficacy at low EC values because it has a higher charge density and greater solvated coil diameter than A110.

Table 4. Yearly and total 7-yr cumulative runoff soil losses for each treatment. Values in parentheses are the standard errors.

Year	Cumulative runoff soil losses		
	Control	A1883	A110
	Mg ha^{-1}		
1993	4.02 (0.32)	1.80 (0.38)	1.19 (0.21)
1994	7.25 (0.59)	2.86 (0.65)	2.50 (0.26)
1995	27.9 (5.6)	3.45 (0.84)	2.50 (0.26)
1996	2.93 (0.60)	0.11 (0.02)	0.45 (0.03)
1997	2.89 (0.38)	0.22 (0.09)	1.18 (0.45)
1998	7.18 (0.42)	0.19 (0.09)	0.28 (0.09)
1999	6.64 (0.87)	0.44 (0.14)	0.86 (0.25)
7-yr total	58.9	9.1	13.0

It seems remarkable that such subtle changes in irrigation water EC may alter WSPAM's effectiveness, even by the relatively small amounts observed over the testing period. However, a subsequent laboratory experiment, which examined the effects water EC on WSPAM-induced kaolinite flocculation, confirmed that flocculation activity varied substantially in the 0.01 to 0.07 S m^{-1} EC range and that two optima occurred, one between 0.02 and 0.035 S m^{-1} and another between 0.035 and 0.05 S m^{-1} (1997, unpublished data). More experimentation is needed to confirm this potential EC effect, as the WSPAM's erosion control efficacy may be influenced by several other water quality factors. Water temperature influences infiltration and hence erosion (Lentz and Bjorneberg, 2002). However, when yearly soil-loss reductions were compared with the average season's irrigation water temperature, no relationship was evident (data not shown). Activity of WSPAM can also be affected by changing concentrations of sodium or complexing metal cations, or dissolved organic matter (Henderson and Wheatley, 1987; Lu et al., 2002), but these data were not measured and an alternate data source was not available for comparison.

In general, mean runoff sediment concentrations and runoff soil losses decreased, and WSPAM-induced soil-loss reduction increased with IT as the number of irrigations conducted on an otherwise undisturbed furrow increased (Table 3, Fig. 4D, 4E, 4F). The decrease in soil losses was partly due to the decreasing availability of loose, easily entrained soil present in freshly formed furrows that is systematically removed during each subsequent irrigation; and also due to the general decrease in furrow stream outflow rate that occurred with increasing irrigation number (Table 3, Fig. 4C). Lentz and Sojka (2000) showed that the efficacy of WSPAM treatments was inversely related to furrow outflow rate. However, as indicated in Fig. 4F, the erosion-control efficacy of A110 treatments responded differently to the increasing number of repeat irrigations (IT) than did A1883. The efficacy of both treatments was similar for fresh furrows (~78%), but A110 efficacy increased to 88% by the first repeat (IT = 2), whereas A1883 efficacy did not increase (to 96%) until after 2 or more repeat irrigations (IT = 3). Since there was no corresponding differences in the treatments with regard to furrow outflow (Fig. 4C) or runoff sediment concentration (Fig. 4E), it is not clear why the treatment responses differed.

The treatment-by-year interaction was also significant for mean runoff sediment concentration (Table 2). Its influence on sediment concentration (Fig. 1E) paralleled that of the soil loss parameter (Fig. 1D) indicating that the two parameters were strongly correlated.

Infiltration, Furrow Advance, and Infiltration Fraction

When analyzed together as a class, the net infiltration into A1883 and A110 furrows was 1.08 times greater than that of controls, 39 vs. 36 mm irrigation^{-1} (Tables 2, 3). The seasonal cumulative net infiltration data were also examined as a function of the type of irrigation inflow application used. Recall that, in years 1993 through 1995, initial irrigation inflows for control and WSPAM furrows were set the same. These data were evaluated separately from years 1997 through 1999, where initial inflow rates for WSPAM furrows were set higher than controls (45 L min^{-1} versus 15 L min^{-1}) to exploit WSPAM's erosion-control capability to increase furrow advance and improve water application uniformity. Note also that in later years, irrigation set times were adjusted to make net infiltration amounts similar among treatments. During the early years, when irrigation inflows were equal between treatments, cumulative infiltration in WSPAM furrows was nearly 1.1 times greater than that of controls (Table 5). A similar pattern was produced in years 1997 to 1999, but the difference was not significant.

Furrow advance time, which is largely a function of inflow and infiltration rates occurring during a short period at the start of the irrigation set, was 1.2 times greater for WSPAM than for controls during the early years (Table 5). Thus, when irrigating with nearly sediment-free water, polymer treatments tended to increase infiltration rates, especially early in the irrigation. This infiltration enhancement has been observed by others in fresh furrows (Sojka et al., 2007), except in soils where low permeability seals do not normally form in irrigated furrows (Ajwa and Trout, 2006). The greater inflows applied to WSPAM furrows in years 1997 through 1999 decreased furrow advance times for WSPAM by 62% relative to controls (Table 5). This indicates that the increased inflows were more than sufficient to offset the effects of WSPAM-induced infiltration gains on stream advance.

The infiltration fraction values are normalized with respect to furrow inflow amounts, so experimental effects on infiltration across irrigations and years should be more discernable in these data. During the years when the same irrigation inflow rates were applied to all treatments (1993, 1994, 1995), the seasonal cumulative infiltration fraction for WSPAM furrows was 1.1 times greater than that for controls (Table 5). During years 1997 through 1999, the cumulative infiltration fraction for WSPAM furrows also trended higher than controls, though not significantly so ($P = 0.07$). These results suggest that the WSPAM increases infiltration into these soils, but that effect may be countered somewhat by increasing initial irrigation inflows and hence, decreasing the furrow advance time.

Table 5. The cumulative seasonal net infiltration and infiltration fraction, and furrow advance period given for years when initial irrigation inflows were equivalent among treatments (1993, 1994, 1995) and in later years (1997, 1998, 1999) when initial inflow rates for water-soluble anionic polyacrylamide (WSPAM) furrows were twice that of controls. Infiltration fraction is the proportion of cumulative irrigation inflows that infiltrated into the furrow. Orthogonal comparisons tested for differences between control and pooled WSPAM values.

	Years	
Treatment	1993–1995	1997–1999
	Seasonal cumulative net infiltration, mm	
control	196b†	244a
WSPAM	214a	263a
	Seasonal cumulative infiltration fraction, %	
control	50b	54a
WSPAM	55a	58a
	Furrow advance, min	
control	53b	127a
WSPAM	65a	48b

† If followed by the same letter, treatment values for a given parameter and year group (between rows) are not significantly different ($P \leq 0.05$).

Over all years, a greater proportion of inflowing irrigation water infiltrated into A1883 furrows (58%) than in either control (54%) or A110 furrows (53%) (Table 3). An examination of the year-by-treatment interactions (Fig. 1A) shows that mean A1883 infiltration fraction values exceeded control values in 1994 and 1997, while A110 infiltration fraction values did not differ from controls in any year. It is not entirely clear why A1883 had a greater impact on infiltration fraction than A110. It is possible that the surfactants present in the oil emulsion also acted to enhance infiltration (Karagunduz et al., 2001).

Treatment effects on infiltration fraction were also strongly dependent on IT. In fresh furrows (IT = 1), WSPAM treatments significantly increased infiltration fraction relative to control furrows (Fig. 4A). However, this infiltration benefit declined with repeated irrigations. The decline resulted from an increase in control furrow infiltration and not to a decrease in WSPAM furrow infiltration (with repeated irrigations). The infiltration fraction of controls increased from 47% in fresh furrows to 59% in multiple-repeat furrows, while WSPAM values were relatively unchanged (Fig. 4A). A similar relationship was reported in previous studies (Sojka et al., 1998; Lentz et al., 2000).

This pattern of increasing infiltration has been attributed to the widening or reshaping of control furrows over time (Sojka et al., 1998). However, the phenomenon has also been reported under field conditions in which furrow broadening was minimal or absent (Lentz et al., 2000). Infiltration in control furrows may also increase with repeated irrigations in response to decreasing stream sediment concentrations (Trout et al., 1995). Runoff sediment concentrations were significantly smaller for multiple-repeat furrows than for fresh or first-repeat furrows (Table 3). The reduced sediment load in control furrows would inhibit soil sealing processes (Trout et al., 1995) and may have contributed to the increasing infiltration fractions observed with the increasing number of repeated irrigations. The sediment concentrations in WSPAM furrows, 0.83 and 0.87 g L^{-1} (Table 3), were below the approximately 4 g L^{-1} needed to produce strong surface sealing (Sojka et al., 2007). Hence,

Table 6. The influence of water-soluble anionic polyacrylamide (WSPAM) treatment and field location on crop yield, stand count, and yield gains.† The table gives *P* values for main effect and interaction terms, and an orthogonal contrast comparing control vs. WSPAM treatment classes. Data were derived from ANOVA on individual crops.

Source of variation	Dependent variable					
	Bean			Corn		
	Yield	Stand count	Yield gain†	Yield	Stand count	Yield gain†
	P					
Treatment	***	0.95	**	0.28	0.47	0.06
Field location	0.21	0.15	0.66	0.13	0.43	0.19
Treatment × Field location	*	0.49	0.14	0.27	0.59	0.08
Orthogonal contrast						
Control vs. WSPAMs	***	0.06	**	0.15	0.23	*

* $P \le 0.05$.

** $P \le 0.01$.

*** $P \le 0.001$.

† Yield gain values were derived as the ratio of the WSPAM yield gain to the average control value, where WSPAM yield gain was calculated as the yield difference, WSPAM minus the average control value.

WSPAM infiltration fraction values changed little when sediment concentrations declined in multiple-repeat irrigations (Fig. 4A). Sediment concentrations in freshly formed control furrows averaged 4.6 g L^{-1}. When this concentration declined to 3.46 g L^{-1} in multiple-repeat furrows, it likely resulted in substantial reductions in surface sealing and consequently increased infiltration fraction of controls. Another process that may contribute to the decreased infiltration benefit over repeated irrigations is the degradation of soil structure, which occurs even in WSPAM-treated furrows over repeated irrigations. This breakdown limits the number of macropores available for water infiltration and forces water to flow through the smaller pores. Since the viscous effects characterizing dissolved WSPAM solutions have a greater inhibitory effect on water transport through small pores compared with large ones, infiltration would decrease (Malik and Letey, 1992). However, since infiltration fraction of A110 did not decline with increasing repeated irrigations (Fig. 4A), the importance of this process appears minimal.

The relationship between infiltration fraction and advance period generally differed depending on treatment and irrigation inflow management (Fig. 1A, 1B). When initial inflow rates were moderate (23 L min^{-1}) in 1993 to 1995, the infiltration fraction tended to be positively correlated to advance period regardless of the treatment. During 1997 to 1999, initial inflows for controls were reduced to 15 L min^{-1}, which resulted in a decoupling of the infiltration fraction and advance-period parameters. When initial inflows for WSPAM were set at a relatively high 45 L min^{-1} (during 1997 to 1999), the infiltration fraction appeared to develop an inverse relationship with advance, and not positively related as was seen when initial inflows were moderate.

Finally, note that mean furrow outflow values for treatment interactions with year (Fig. 1C) and IT (Fig. 4C) represent a near-mirror image of the infiltration fraction patterns shown in Fig. 1A and 4A, respectively, indicating a close inverse relationship between the two parameters.

Crop Yields

The A110 and A1883 treatments affected bean and corn yields similarly, and neither treatment nor field location influenced plant stand counts. When analyzed as a class in comparison with controls, the WSPAM treatments produced small but significant yield gains (Table 6) for both bean (14.3%) and corn (4.5%) crops (Table 7). Absolute bean yield values also significantly increased with WSPAM treatment (Table 6). While an increase in mean absolute corn yield for WSPAM treatments relative to controls was observed, the difference was not significant ($P = 0.06$), possibly due to greater variability in corn yield values in comparison with that of bean. Furthermore, absolute bean yields produced by A110 and A1883 treatments differed depending on field location (Table 6). The A110 bean yields in the outflow-half of the field were significantly greater than that of controls (3.2 vs. 2.6 Mg ha^{-1}), while A1883 bean yields in the outflow-half (2.8 Mg ha^{-1}) were similar to those in the respective controls (2.6 Mg ha^{-1}) (Table 7).

Why did WSPAM produce greater crop yields than the controls? One possible explanation is that WSPAM increased nutrient availability to the crop. El-Hady et al. (1990) reported that polymer applications increased extractable P and K values in a sandy soil. However, it is not clear that the same benefit

Table 7. Mean crop yield and yield gain† values for treatments or treatment classes given for the whole field or the individual field locations (inflow-half vs. outflow-half of the furrow-irrigated field).

Treatment	Bean‡				Corn‡			
	Whole field		By field location		Whole field		By field location	
	Treatment class	Individual treatment	Inflow-half	Outflow-half	Treatment class	Individual treatment	Inflow-half	Outflow-half
	Yield, Mg ha^{-1}							
Control	2.7b§	2.7b	2.8B¶	2.6B	20.5a	20.5	19.8	21.2
A1883	3.1a	3.0a	3.2A	2.8B	21.4a	21.2	20.8	21.6
A110	3.1a	3.2a	3.1A	3.2A	21.4a	21.7	20.1	23.2
	Yield gain, %†							
Control	0b	0b	0	0	0b	0	0	0
A1883	14.3a	11.6a	16.2	7.1	4.5a	3.4	4.1	2.3
A110	14.3a	17.7a	11.7	23.7	4.5a	5.5	1.3	9.8

† Yield gain values were derived as the ratio of the treatment yield gain to the average control value, where yield gain was calculated as the yield difference, treatment minus the average control value.

‡ Mean crop stand counts were unaffected by treatment or field location: 41.5 plants $plot^{-1}$ for bean and for 46.3 plants $plot^{-1}$ for corn.

§ If followed by the same lowercase letter, individual treatment or treatment class values for a given variable and crop were not significantly different ($P \le 0.05$). Not displayed if effect was not significant in the ANOVA (Table 6).

¶ If followed by the same uppercase letter, treatment field location values for a given variable and crop were not significantly different ($P \le 0.05$). Not displayed if effect was not significant in the ANOVA (Table 6).

would be realized in the silt loam soils used here. It is also possible that the yield increase was related to soil water dynamics. The polymer increased infiltration fraction relative to controls in fresh furrows. Furthermore, WSPAM increases lateral movement of water at the soil surface, so that more water moves toward the planted row compared with controls (Lentz et al., 1992). Yoder and others (1996) showed that water movement is generally downward in soil beneath untreated wheel-trafficked furrows, with limited horizontal water transport. This implies that dissolved nutrients more readily move downward in the soil profile than laterally.

A series of regression analyses were conducted to evaluate the relationship between crop yield gains and cumulative infiltration over the entire furrow. Results for each treatment and crop produced no significant positive relationships between yield gain and infiltration (data not shown), which implies that soil–water dynamics may have had little influence on crop yields. This analysis would have been more conclusive, however, if we had been able to evaluate the infiltration and yield gain relationships on an individual field location basis (infiltration data for individual field locations was not collected). Further research is needed to better understand WSPAM effects on crop productivity. This research should ascertain how WSPAM effects soil water distribution within the soil profile at both inflow and outflow field locations, and determine if soil water availability for relatively shallow-rooted bean crops may differ from that which is accessible to more deeply-rooted corn.

It is not clear why the absolute bean yields for A1883 decreased from inflow-half to ouflow-half field locations, while those of A110 did not (Table 7). Because the proportion of inflowing water that infiltrated was greater for A1883 than A110 (Table 3), it may be that A1883 furrow streams at outflow-half field locations were smaller than those for A110. Smaller furrow streams would have resulted in less infiltration and the yield reduction may have been a response to reduced water availability.

Yield gains observed for individual crops indicate that the cost of the WSPAM application may be reimbursed by an ensuing gain in crop yields. In this study, the mean WSPAM application was 11.5 kg ha^{-1} yr^{-1}, whereas if the 23-L-min^{-1} water inflows used in the first few years were employed in all six cropped years, the total WSPAM used would have been 7.2 kg ha^{-1} yr^{-1}. At the current price of \$8.80 kg^{-1} for A110 (solid WSPAM), this represents a cost of \$101 ha^{-1} yr^{-1} for this study, or as little as \$63 ha^{-1} yr^{-1} had the low inflow rate been used in all years. This cost would double if A1883 (inverse emulsion WSPAM) was employed instead of A110. A 14.3% yield increase (Table 7) would produce an extra 0.43 Mg ha^{-1} yr^{-1} in bean and a 4.5% yield increase (Table 7) would produce an extra 0.95 Mg ha^{-1} yr^{-1} in standing corn. Local market prices realized over the last 2 yr have ranged from \$360 to \$725 Mg^{-1} (\$20 to \$40 hundredweight^{-1}) for dry bean and from \$36 to \$50 Mg^{-1} (\$40 to \$55 ton^{-1}) for standing corn. Therefore, the additional yields could generate an additional \$155 to \$311 ha^{-1} yr^{-1} for the bean and \$34 to \$48 ha^{-1} yr^{-1} for the standing corn crops. Hence, the use of WSPAM in furrow irrigation not only generates benefits related to the conservation of sediment, water, and soil nutrients, but potentially provides yield enhancement and monetary reimbursement. The latter incentive may encourage more producers to incorporate this conservation practice into their management programs.

It should be noted that WSPAM treatments do not produce an increase in net infiltration in some soils. Ajwa and Trout (2006) reported no increased infiltration when emulsion WSPAM was applied to irrigation water supplying nearly level furrows formed in loamy sands. It is not clear if the polymer would produce crop yield gains under these circumstances.

CONCLUSIONS

This 7-yr experiment compared the effectiveness of A1883 (inverse emulsion) and A110 (solid) WSPAM formulations for use in managing soil erosion and infiltration in irrigation furrows. Aqueous stock solutions made up from the two materials were injected into the irrigation water during furrow advance to obtain a furrow stream WSPAM concentration of 10 mg L^{-1}.

Both formulations demonstrated equal effectiveness for controlling runoff soil losses. They reduced overall soil losses by 84% per irrigation and total cumulative soil losses by an average 47.8 Mg ha^{-1} during the 7-yr period. However, there is some evidence that their efficacy for erosion control may be influenced by changes in salt concentrations in the irrigation water as measured by EC. Under conditions of this study, optimal irrigation water ECs appear to be centered around 0.037 S m^{-1}. Additional study is needed to confirm these observations on EC effects.

Overall effectiveness of the inverse-emulsion formulation (A1883) for increasing the infiltration fraction (infiltration as a percentage of inflow) was greater than that of the granular form (A110), though both forms succeeded in increasing infiltration fraction during the irrigation of fresh or newly formed furrows. Some irrigators may consider using the inverse emulsion (A1883) instead of the solid (A110) as a way to increase water infiltration into field soils that are prone to surface sealing. These irrigators need to be cognizant of two disadvantages associated with the use of inverse emulsion for this application: (i) its greater cost (twice that of the solid WSPAM); and (ii) because it includes components not found in granular WSPAM, the oil-based inverse emulsions are not as environmentally benign as granular WSPAM formulations (Weston et al., 2009), hence additional precautions are necessary to prevent the inverse-emulsion from entering nearby natural streams by way of irrigation return flow.

The cost of WSPAM applications may be partially or fully offset by yield gains produced. Compared with controls, overall crop yields increased for the WSPAM treatments as a whole, 1.14 times greater for bean, and 1.05 times greater for silage corn. More study is needed to understand how WSPAM may influence productivity.

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