Managing Runoff Water Quality from Recently Manured, Furrow-Irrigated Fields

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Nutrient losses in furrow irrigation runoff potentially increase when soils are amended with manure. We evaluated the effects of tillage, water-soluble polyacrylamide (WSPAM), and irrigation management on runoff water quality during the first furrow irrigation on a calcareous silt loam soil that had received 45 Mg ha^{-1} (dry wt.) dairy manure applied in the fall. In Exp. 1, the amended soil was rototilled and irrigated that fall; furrow inflows were either treated with 10 mg L^{-1} WSPAM injected into furrow inflows only during furrow advance (Fall-WSPAM), or were untreated (Fall-Control). In Exp. 2, the first irrigation on the amended soil was delayed until the following spring and treatments included rototilled WSPAM (Spring-WSPAM), with WSPAM applied as in Exp. 1, and untreated rototilled (Spring-Control) or moldboard-plowed soils (Spring-Plow). Experiment 3 also delayed irrigation until spring and compared conventional vs. buried lateral furrow irrigation systems. We measured sediment, dissolved organic C (DOC), NO_3–N, NH_4–N, dissolved reactive P (DRP), and total P (TP) concentrations in irrigation furrow runoff. Runoff mass losses from Fall-Control furrows were relatively large: sediment, 4505 kg ha^{-1}; DOC, 10.7 kg ha^{-1}; NO_3–N, 28.1 g ha^{-1}; NH_4–N, 68.1 g ha^{-1}; DRP, 132 g ha^{-1}; and TP, 3381 g ha^{-1}. Delaying the first irrigation until spring or treating the fall irrigation with WSPAM reduced runoff component losses by 80 to 100% relative to Fall-Control. The Spring-Plow treatment reduced runoff DRP mass losses by ~60% compared with Spring-Control. The buried lateral furrow system decreased runoff mass losses for sediment, DOC, and TP by >80% relative to conventional irrigation. This research demonstrated that several management practices may be successfully used to substantially reduce offsite nutrient transport during the first irrigation on furrow-irrigated, manure-amended fields.

Abbreviations: DOC, dissolved organic carbon; DRP, dissolved reactive phosphorus; EC, electrical conductivity; TP, total phosphorus; WSPAM, water-soluble polyacrylamide.

Water quality issues related to agricultural irrigation and drainage remain some of the most challenging problems confronting agricultural and engineering professionals (Tanji and Keyes, 2002). Irrigation runoff transports materials from cropped fields to offsite environments, where they may have negative ecological impacts. Excess irrigation water is allowed to run off furrow-irrigated fields to improve water application uniformity (Bishop et al., 1967). Several components in the runoff water pose a concern, including sediments, organic C, salts, nutrients such as NO_3, NH_4, K, and P, trace elements, pesticides, and microorganisms (Bondurant, 1971; Turner et al., 1980; Bjorneberg et al., 2002; Tanji and Keyes, 2002; Causapé et al., 2004). Sediment concentrations of 1000 to 10,000 mg L^{-1} are common in runoff from recently tilled, furrow-irrigated fields (Berg and Carter, 1980). The transported sediment and associated organic matter are an important source of N and P (Heathwaite and Johnes, 1996), which play a dominate role in the eutrophication of freshwater and ocean ecosystems (Correll, 1998).

Total P concentrations in furrow irrigation runoff are linearly related to runoff sediment and range from 0.3 to 17 mg L^{-1} (Fitzsimmons et al., 1972; Westermann

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et al., 2001). Dissolved reactive P concentrations in runoff are less correlated with sediment, and irrigation mean values range from 0.04 to 0.18 mg L^{-1} (Fitzsimmons et al., 1972; Westermann et al., 2001; Bjorneberg et al., 2006; Lentz and Lehrsch, 2010). Runoff DRP was found to be influenced by furrow length, the residence time of water in the furrow (stream velocity), the quantity of crop residue exposed in the furrow (Bjorneberg and Aase, 2004; Westermann et al., 2001), and infiltration fraction (Lentz and Lehrsch, 2010). Fitzsimmons et al. (1972) reported mean N concentrations in a random sampling of surface irrigation inflow and runoff waters from 30 farms in southwest Idaho. Nitrate-N concentrations were 1.04 mg L^{-1} in inflows and 1.21 mg L^{-1} in runoff, NH_4–N concentrations were 0.41 mg L^{-1} in inflows vs. 2.02 mg L^{-1} in runoff, and organic N concentrations were 0.64 mg L^{-1} in inflows vs. 1.88 mg L^{-1} in runoff.

Nutrient additions to the soil, whether from animal wastes or inorganic fertilizers, generally increase nutrient runoff losses in irrigation return flows; however, the quantity lost varies depending on the type of amendment, nutrient, and timing of application (Lentz and Lehrsch, 2010). When amendments were incorporated into soil, Lentz and Lehrsch (2010) concluded that runoff losses of soil DRP and inorganic N were substantially influenced by biocycling processes, which in turn were influenced by application timing and environmental conditions. Under rainfed conditions, tillage following P application can decrease runoff DRP losses by reducing the contact between the applied nutrient and surface waters, but increase TP losses by increasing sediment in the runoff (Bundy et al., 2001; Kimmell et al., 2001).

Reactive P in runoff from flood-irrigated forage crops fertilized with unincorporated phosphate fertilizer decreased as the lag time before the first irrigation increased (Bush and Austin, 2001; White et al., 2003). A longer lag time before irrigation allowed more complete dissolution of fertilizer pellets and movement of the nutrient into the surface soil. In addition, P losses in runoff from such fields decreased with increasing number of irrigations (Austin et al. (1996). The influence of grass cutting and cow stocking density on P and N in runoff from a flood-irrigated perennial pasture was evaluated by Mundy et al. (2003). The researchers observed that runoff TP from pastures increased as the stocking rate increased and concluded that the transported P originated from several pasture sources, including the soil, vegetation, and cow feces.

Little research has evaluated the effect of irrigation timing or tillage management on nutrient runoff losses from recently manured, furrow-irrigated fields. In a 2-yr study, Lentz and Lehrsch (2010) monitored runoff from fall-applied vs. spring-applied manure; however, manure rates between the two applications were dissimilar. Management effects on runoff water quality from manure-amended fields are well documented for rainfall events (Zhao et al., 2001; Andraski et al., 2003; Little et al., 2005; Smith et al., 2007; Soupir et al., 2006; Gilley et al., 2007; Kaiser et al., 2009). The entire soil surface typically interacts with applied water during rainfall and flood irrigation events, while during furrow irrigation, only that fraction of the soil surface within the furrows interacts with the applied water. In addition, the potential for nutrient transport into furrow-irrigated soils can be greater than in rainfed soils. An equivalent water application in furrow-irrigated soils requires a greater infiltration event than in rainfed soils because the area of soil subject to infiltration is less under furrow irrigation. Commonly the first runoff event occurring after manure application produces the greatest nutrient losses, whether it is rainfall (Pote et al., 2003) or irrigation induced (Mundy et al., 2003; Bush and Austin, 2001).

A number of researchers have evaluated the use of water-soluble anionic polyacrylamides (WSPAM) to improve runoff water quality from treated irrigation furrows (Lentz et al., 1998; Meral et al., 2004; Goodson et al., 2006; Oliver and Kookana, 2006; Szögi et al., 2007), although results have been inconsistent. A buried lateral furrow irrigation system is a gravity-based alternative to conventional furrow irrigation (Worstell, 1976, 1979). A buried system effectively reduces the length of the irrigation furrow by splitting it into two or three coterminous segments. These are sequentially irrigated, typically using an automated valving system. Each segment is irrigated using a furrow stream that has a smaller flow rate and stream velocity than that used in the original full-length irrigation furrow. The smaller furrow stream is less erosive and produces less runoff, which decreases soil entrainment and transport of sediment off the field (Worstell, 1976); hence, a buried lateral system can potentially reduce nutrient losses in irrigation runoff. A buried lateral system is also more efficient than conventional furrow irrigation due to reduced runoff volumes (Worstell, 1976).

Potential nutrient losses from manure-amended, furrow-irrigated fields need to be managed in a manner that will minimize the loss of these valuable and expensive field resources and protect the ecology of natural water bodies that receive irrigation runoff; however, little data comparing the effects of furrow irrigation practices on nutrient losses have been published. In this study, we compared the effect of several soil and irrigation management options on runoff nutrient and DOC losses from the first irrigation on a furrow-irrigated field amended with manure in late summer. Our objectives were (i) to determine the effect of WSPAM on rototilled soils when the first irrigation was applied in fall or spring; (ii) to determine the impacts of rototill vs. moldboard plow tillage before the first irrigation in the spring; (iii) to compare the influence of buried vs. conventional irrigation systems when the first irrigation is applied in the spring, and (iv) evaluate the effect of delaying the first irrigation after manure application from fall to spring.

MATERIALS AND METHODS

Experimental Design

The study consisted of three experiments conducted in three adjacent, subdivided areas within a furrow-irrigated field. All plots were treated with manure in late summer. The design used in each experiment was a randomized complete block with three replicates. Details of the treatments used in the experiments are presented in Table 1.

Table 1. Description of treatments in each of the three experiments.

Experiment and treatment	Tillage†	WSPAM‡	Irrigation	Time of manure application	Monitored first irrigation	Rainfall received§
						mm
Exp. 1						
Fall-Control	rototill	none	furrow	Aug. 1999	20 Sept. 1999	1.0
Fall-WSPAM	rototill	10 mg L^{-1} in inflows	furrow	Aug. 1999	20 Sept. 1999	1.0
Exp. 2						
Spring-Control	rototill	none	furrow	Aug. 1999	30 May 2000	163.6
Spring-WSPAM	rototill	10 mg L^{-1} in inflows	furrow	Aug. 1999	30 May 2000	163.6
Spring-Plow	Moldboard	none	furrow	Aug. 1999	30 May 2000	163.6
Exp. 3						
Conventional	rototill	none	furrow	Aug. 1999	24 May 2000	164.1
Buried lateral	rototill	none	furrow, buried lateral	Aug. 1999	24 May 2000	164.1

† Rotary tillage to 0.1-m depth or moldboard plowing to 0.18-m depth was done after manure was applied and incorporated (offset disking to 0.1-m depth).

‡ From the start of the irrigation, water-soluble polyacrylamide (WSPAM) was injected into furrow inflows at the given active ingredient concentration. The WSPAM injection was curtailed after the furrow stream advanced to the end of the furrow and untreated irrigation water was applied for the remainder of the set.

§ Rainfall received by plot soils between the date of manure application and the monitored first irrigation.

Experiment 1

The plot was irrigated in the fall and included an untreated control and a WSPAM treatment. The WSPAM was added to furrow inflows at a concentration of 10 mg L^{-1} a.i. during the furrow advance phase, and the inflows were untreated for the remainder of the irrigation. Each experimental unit consisted of a single irrigation furrow.

Experiment 2

The plot was irrigated in the following spring and included three treatments: (i) rotary tillage to 0.1-m depth before planting followed by a WSPAM-treated furrow irrigation (applied as in Exp. 1); (ii) rotary tillage to 0.1-m depth before planting and untreated furrow irrigation; and (iii) moldboard plow tillage to 0.18-m depth before planting with an untreated furrow irrigation. Each experimental unit consisted of a single irrigation furrow.

Experiment 3

The plot was irrigated in the following spring and included two treatments: conventional furrow irrigation and buried lateral furrow irrigation (described below). Each experimental unit consisted of a contiguous block of four irrigated furrows.

Site, Soils, Manure, and Polymer

Three experimental plots were established in 1999 on Portneuf silt loam soil (a coarse-silty, mixed, superactive, mesic Durinodic Xeric Haplocalcid) with 4% slopes, and located 8.7 km south-southwest of Kimberly, ID. The surface soil (0–15 cm) is a silt loam and contains on average 100 g kg^{-1} clay, 650 g kg^{-1} silt, 250 g kg^{-1} sand, 10 g kg^{-1} organic matter, and 5% $CaCO_3$ equivalent. The soil has a cation exchange capacity of 190 $mmol_c$ kg^{-1}, saturated-paste-extract electrical conductivity (EC) of 0.07 S m^{-1}; exchangeable Na percentage of 1.5; and pH of 7.7 (H_2O saturated paste). The mean soil test P value for the three plots, measured after manure amendment and before irrigation, was 55.0 mg kg^{-1}. Stockpiled solid manure from dairy cattle (*Bos* spp.) was applied to all experimental plots (described below). It contained an average of 16.2 g kg^{-1} total N and 243 g kg^{-1} total C (determined on a freeze-dried sample with a Thermo-Finnigan FlashEA1112 CNS analyzer, CE Elantech, Lakewood, NJ).

The linear anionic polymer was obtained from CYTEC Industries, Water Treatment and Paper Chemicals Division (now Kemira Water Solutions, Stamford, CT). The Superfloc A110 flocculant was a solid formulation of acrylamide–sodium acrylate copolymer with 15 to 20 × 10^6 Da molecular weight (Da = g mol^{-1}, derived from viscosity measurements) and 18% charge density. It included 80% a.i., 5 to 10% water, plus a salt that acted as a dissolution aid. Stock solutions of the WSPAM (2400 mg L^{-1} a.i.) were made up from tap water (EC = 0.09 S m^{-1}, Na adsorption ratio = 1.5) before the irrigation and allowed to stand overnight before use.

Site Preparation and Field Operations

The 3-ha field containing the three experimental plots had not received a manure application for at least 10 yr and was not planted to crops in the previous 2 yr. In summer 1999, the field was smoothed using a leveling blade. Manure was applied at 45 Mg ha^{-1} (dry wt.) to the entire field in early August 1999 using a commercial spreader truck equipped with rooster-comb beaters. The manure was incorporated with several passes of an offset disk (0.1-m depth) in late August 1999. In April 2000, the field was planted with a mixture of alfalfa (*Medicago sativa* L.) and various pasture grasses in combination with oat (*Avena sativa* L.). Planting was completed in a single pass with a combination roller harrow and planting drill unit.

Experiment 1 was established in a plot 23 m wide with furrows 177 m long. The plot was rototilled in mid-September 1999 to 0.1-m depth and furrows approximately 0.15 m deep were constructed in the plot using weighted v-shaped tools attached to the tractor's rear tool bar. Irrigation furrows were spaced 1.52 m apart and were not wheel trafficked. The Exp. 1 plots were conventionally furrow irrigated on 20 Sept. 1999, thus the soils in this plot were fallow at the time of this monitored first irrigation. The manure-amended soil had received little rainfall before the irrigation (Table 1).

Experiment 2 was established on a 14-m-wide and 177-m-long plot. The plot was rototilled to 0.1-m depth in mid-May 2000 except for three 1.5-m-wide strips, one located randomly in each of the three blocks. This strip was moldboard plowed to 0.18-m depth. The plot was then planted to a mixed alfalfa–grass–oat crop and furrows were cut in the plot using the same approach used in Exp. 1. The plot in Exp. 2 was conventionally furrow irrigated for the first time after manure application on 30 May 2000. The plot had received 163.6 mm of rainfall between the time the manure was applied and the time of the irrigation (Table 1). Non-wheel-trafficked furrows were irrigated and monitored. Irrigation inflows for some WSPAM furrows were adjusted upward early in the irrigation to speed furrow advance and improve water application uniformity. The upward adjustment of inflows is commonly practiced by irrigators because WSPAM tends to increase water infiltration in the treated furrows (Lentz and Sojka, 2000; Oliver and Kookana, 2006; Meral et al., 2004). Increasing inflows into these slowly advancing furrows increased the total inflows for WSPAM relative to the other treatments, but also increased the WSPAM furrow stream velocities, which would otherwise be drastically lower than in the untreated furrows.

Experiment 3 was conducted on a 37-m-wide and 177-m-long plot. In mid-May 2000, the field was rototilled to 0.1-m depth and furrows were cut in the plot after planting using the same approach used in Exp. 1. Only non-wheel-trafficked furrows were irrigated and monitored. One of the furrows in the conventional block was monitored. Runoff rates in the buried lateral furrows were low due to the lower inflow rates used relative to the conventional furrows. Hence, the four furrows in the buried lateral experimental unit were merged into one channel at the tail end of the furrow. This allowed more accurate flume measurement of flow rates and provided a more representative sample of runoff components. The plot had received 164 mm of rainfall between the time manure was applied and the irrigation (Table 1).

Irrigation

The Snake River water used for irrigation had an average EC of 0.04 S m^{-1}, a Na adsorption ratio of 0.06, and had little sediment (<500 mg L^{-1}). The conventional irrigation system consisted of a gated pipe, which conveyed irrigation water across each of the plots at the head, or inflow end, of the furrows. Adjustable spigots in the gated pipe supplied 15 to 23 L min^{-1} water to each furrow. After traversing the entire length of the furrow, the irrigation water entered a tail-water ditch that ran perpendicular to the furrows at the bottom of the plots.

The buried lateral system included a gated pipe at the inflow end of the furrow and two 0.075-m-diam. polyvinyl chloride pipes aligned perpendicular to the furrows and buried at 0.3-m depth. One of these buried laterals was located at a distance of one-third of a furrow length and a second at two-thirds of a furrow length downfield from the furrow inflow end. A single orifice was drilled through the upper surface of each buried lateral where it intersected furrows located in the buried lateral experimental units. Each buried lateral was connected through a valve to the main irrigation water supply. The length of each of the three furrow subunits (177 m ÷ 3 = 59 m) and furrow inflow rate used in the buried lateral system were selected to minimize furrow erosion (Worstell, 1976). A more detailed description of the system design was provided by Worstell (1976).

During irrigation of the buried system treatment, water was cycled to individual gated pipe or buried lateral pipes sequentially such that water flowed into the furrows at 4 L min^{-1}, one-quarter the rate used for conventionally irrigated furrows. The length of the buried lateral irrigation sets was extended so that it and the conventional treatments applied equal total inflow amounts. We manually diverted water to each of three buried-system inflow locations every 8 h on average. Water flowing into a buried lateral pipe jetted to the soil surface at the mid-field locations, flowed into the furrows located above the pipe orifices, then advanced downslope.

Furrow inflows, stream runoff rates, and sediment concentrations were measured during each irrigation. Runoff rate measurements and runoff water samples were taken for sediment concentration determinations at 0.5-h intervals after irrigation runoff began, every hour during the mid-irrigation period, and every 2 h thereafter, when irrigation runoff and sediment loads had stabilized (typically about 7 h after runoff began). Inflows were measured by timing the filling rate of a known volume, and runoff was measured with long-throated v-notch flumes. Although a flume measurement has a slightly greater uncertainty than that obtained from the volume-filling rate method, flume installation was less intrusive at furrow outflow positions and determinations were more rapid compared with the volume-fill approach.

Sampling and Analyses

Before irrigation, we collected soil samples from the 0- to 15-cm depth to characterize soil test P. Five to six samples from each block in each experimental plot were composited and analyzed. Soil P was extracted using a 0.5 mol L^{-1} $NaHCO_3$ solution (Olsen et al., 1954) and P was determined using the ascorbic acid method (Watanabe and Olsen, 1965).

Runoff water quality samples were collected from the outflow measuring flumes at the end of monitored furrows in each irrigation. In Exp. 1, six runoff water quality samples per irrigation were collected at 5 min and 0.5, 2, 8, 14, and 24 h after furrow advance. These data verified the results from other studies (Lentz and Lehrsch, 2010) showing that the greatest changes in constituent concentrations occurred in the first 4 to 5 h after runoff began, with only minor changes occurring thereafter. Furthermore, the 0.5-h sample time was not as definitive as a 1-h sampling time because runoff rates early in the runoff period were relatively small. Therefore, in Exp. 2, the 24-h sample time was dropped and a 1-h time was substituted for the 0.5-h sample. In Exp. 3, water quality sampling was as in Exp. 1 except the 24-h sampling time was eliminated. Three to six irrigation inflow samples were also collected during irrigations to determine nutrient background concentrations. Portions of the runoff samples were filtered through 0.45-μm Millipore membranes. Runoff and inflow samples were stabilized with a saturated H_3BO_3 solution (1 mL per 100-mL sample) and stored at 4°C until analysis. We determined TP in the unfiltered samples by persulfate digestion (American Public Health Association, 1992) and analyzed filtered samples for DRP (Watanabe and Olsen, 1965), NO_3–N, and NH_4–N using flow injection analysis and colorimetric methods (Mulvaney, 1996), and DOC using a Shimadzu TOC-5000A total organic C analyzer.

Calculations and Statistical Analysis

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 cali-

Table 2. The influence of treatment on furrow infiltration, and runoff component concentrations and cumulative component losses in irrigation furrow runoff. The *P* values for treatment effects were derived from an ANOVA; the source of variation for each experiment was treatment.

	P > *F*†															
					Mean irrigation runoff conc.						Cumulative mass loss per irrigation					
Exp.	Total inflow	Total runoff	Mean runoff rate	Infiltration	Sediment	DOC	NO_3–N	NH_4–N	DRP	TP	Sediment	DOC	NO_3–N	NH_4–N	DRP	TP
1	0.18	0.08	*	0.06	**	***	0.22	***	0.07	**	*	**	*	**	*	*
2	0.07	**	**	0.11	***	0.14	0.27	0.08	0.19	***	**	*	0.22	0.15	**	***
3	0.04	0.32	*	0.25	*	0.09	0.21	*	0.71	*	***	*	0.26	0.07	0.52	*

* Significant at $P \le 0.05$.

** Significant at $P \le 0.01$.

*** Significant at $P \le 0.001$.

† DOC = dissolved organic C; DRP = dissolved reactive P; TP = total P.

bration functions for each irrigation and treatment and calculated the net infiltration and runoff. The WASHOUT program computes the net infiltration volume for individual furrows by subtracting the total runoff volume from the total inflow volume, where inflow and runoff volumes were computed by integrating the inflow- and runoff-rate curves with time. We defined the mean runoff rate as the total runoff volume divided by the total runoff period. The net infiltration depth (i.e., infiltration on an area basis) was calculated by dividing the net infiltration volume by the field area watered by the irrigation furrow, where the watered area was the product of the spacing between irrigation furrows and the furrow length. Infiltration as a percentage of irrigation inflow (infiltration fraction) was calculated as 100 times the quotient of the net furrow infiltration divided by the net inflow.

Reported sediment and nutrient concentrations and values used in mass-loss computations were adjusted for inflow concentrations, so furrow losses represent only those losses resulting from treatments. Furrow sediment and nutrient losses were computed by WASHOUT, which calculated sediment and nutrient loads in the furrow stream runoff and integrated component losses across the duration of the irrigation. Cumulative TP, DRP, NO_3–N, NH_4–N, and DOC mass losses per irrigation were computed with the assumption that runoff constituent concentrations remained constant between sampling intervals. Mean sediment and nutrient concentrations per irrigation were computed as the total mass loss divided by the total runoff volume.

Irrigation and water quality data from each experiment were analyzed via ANOVA, PROC Mixed (SAS Institute, 1999) and the results are reported in Table 2. The model included treatment as the fixed effect and block with its associated interaction as random effects. Response variables for runoff nutrient concentrations and losses for individual irrigations were transformed (square root or $\log_{10}$) to stabilize the variances. Treatment means and confidence limits were back-transformed to the original units for reporting. Treatments from fall 1999 and spring 2000 were compared by examining the 95% confidence intervals on the response means, i.e., for irrigation and runoff nutrient concentration and loss values. Confidence limits for treatment mean values were computed for each experiment as part of the ANOVA analysis. (If the confidence interval of one treatment mean overlaps the mean value of another treatment, the two treatment means are not significantly different.) All analyses were conducted using a $P = 0.05$ significance level.

RESULTS AND DISCUSSION

The results of the statistical analyses for the three experiments are reported in Table 2, component runoff data are reported in Table 3, and infiltration and runoff data in Table 4. Differences in irrigation inflows between treatments in each experiment were small or not significant (Table 2), thus when total runoff or infiltration differed between controls and treatments, it was considered to be a direct treatment effect.

Table 3. Furrow runoff component concentrations and cumulative mass loss per irrigation.

Treatment	Irrigation runoff component conc.†						Cumulative mass loss per irrigation					
	Sediment	DOC	NO_3–N	NH_4–N	DRP	TP	Sediment	DOC	NO_3–N	NH_4–N	DRP	TP
	g L^{-1}	mg L^{-1}					kg ha^{-1}	g ha^{-1}				
							Exp. 1, Fall irrigation					
Control, rototill	13.8 a‡	34.8 a	0.08	0.22 a	0.47	10.1 a	4505 a	10.7 a	28.1 a	68.1 a	132 a	3381 a
WSPAM§, rototill	0.01 b	6.7 b	0.07	0.11 b	0.14	0.23 b	0.1 b	0.6 b	6.7 b	10.3 b	12.7 b	20.3 b
							Exp. 2, Spring irrigation					
Control, rototill	3.4 a	2.4	0.01	0.04	0.11	5.7 a	838 a	0.42 a	0.9	10.2	25.4 a	1378 a
Control, plow	3.2 a	1.3	0.02	0.05	0.07	3.7 a	491 a	0.20 a	3.9	6.5	10.6 b	617 a
WSPAM, rototill	0.06 b	0.5	0.01	0.03	0.07	0.3 b	7.1 b	0.05 b	0.8	3.4	6.9 b	32 b
							Exp. 3					
Conventional irrigation	4.7 a	0.45	0.000	0.07 a	0.04	3.2 a	568 a	0.06 a	0.03	9.8	6.8	405 a
Buried lateral irrigation	0.9 b	0.09	0.004	0.03 b	0.03	1.0 b	60.2 b	0.006 b	0.68	3.0	2.4	75 b

† DOC = dissolved organic C; DRP = dissolved reactive P (filtered sample); TP = total P (unfiltered sample).

‡ If followed by a different lowercase letter, individual treatment values for a given experiment are significantly different (P ≤ 0.05). Not displayed if effect was not significant in the ANOVA (Table 2).

§ WSPAM = water-soluble polyacrylamide.

Table 4. The influence of treatments on furrow runoff, infiltration, and stream advance times.

Treatment	Total Flow		Infiltration	Mean runoff rate	Infiltration fraction	Advance time
	Inflow	Runoff				
	mm			L min^{-1}	%	min
			Exp. 1, Fall irrigation			
Control, rototill	83.8	32.1	51.8	8.7 a†	0.61	259
WSPAM‡, rototill	87.8	9.9	77.9	2.2 b	0.89	261
			Exp. 2, Spring irrigation			
Control, rototill	73.1	23.3 a	49.8	5.1 a	0.67 b	256
Control, plow	69.6	16.5 ab	53.1	3.7 ab	0.73 ab	189
WSPAM, rototill	89.6	11.4 b	77.0	2.9 b	0.85 a	299
			Exp. 3			
Conventional irrigation	55.8 b	13.7	42.1	3.6 a	0.75	§
Buried lateral irrigation	57.1 a	10.0	47.1	1.2 b	0.83	§

† If followed by a different lowercase letter, individual treatment values for a given experiment are significantly different ($P \geq 0.05$). Not displayed if effect was not significant in the ANOVA (Table 2).

‡ WSPAM = water-soluble polyacrylamide.

§ Effective furrow length differed between conventional and buried lateral treatments, so advance time was not comparable.

Experiment 1: Fall Water-Soluble Polyacrylamide Effects

It was apparent, given the cloudy appearance and dark discoloration of runoff from the control furrows in the fall-irrigated, manure-amended soils (Fall-Control), that sediment and DOC concentrations were high (Berg and Carter, 1980). Compared with control furrows, the Fall-WSPAM treatment reduced the mean runoff rate by 75% (Table 4) and decreased runoff concentrations of sediment by 99.9%, DOC by 81%, NH_4–N by 50%, and TP by 98% (Table 3). The combined effect of a lower average runoff volume and reduced nutrient concentrations substantially reduced component mass losses in WSPAM furrows relative to the control. The WSPAM reduced cumulative mass losses for sediment 100%, TP 99%, DOC 94%, NO_3–N 76%, NH_4–N 85.1%, and DRP 90.4% (Table 3).

The WSPAM treatment reduced runoff nutrient losses primarily by controlling erosion and sediment entrainment in the furrow stream and by reducing the runoff volume. Polymer application increased the soil aggregate stability (Shainberg et al., 1992) and decreased soil dispersion, particularly during the rapid wetting event that occurs in furrows when the flow is initiated (Lentz et al., 1992). Sojka et al. (1998) reported that WSPAM treatment nearly doubled the percentage of water-stable aggregates present in treated furrow soils relative to untreated soils. By reducing entrained sediment in the furrow stream by 99%, WSPAM greatly reduced the soil mass and surface area that was exposed to the flowing water. The transported sediment is a source of DOC (Laegdsmand et al., 2005) and nutrients such as TP (Berg and Carter, 1980; Sharpley et al., 1992), and DRP (Logan, 1982), but the sediment concentration also indicates the vigor of the mixing processes occurring at the soil–water interface in the furrows. By decreasing sediment loads, WSPAM limited the dissolution, diffusion, and desorption reactions, which release soil-associated DOC and nutrients into the furrow stream. The polymer's soil-stabilization properties also promote increased furrow infiltration, particularly in freshly formed furrows (Lentz et al., 1992; Lentz and Sojka, 2000; Sojka et al., 1998). The resulting decrease in mean runoff volume, compared with control furrows, contributed to the decrease in runoff component mass losses. By decreasing the mean furrow runoff rates relative to the control, WSPAM also reduced the size and hence wetted perimeter of the furrow stream. This decreased the stream's exposure to soils along the furrow reach and hindered the transfer of soil nutrients to the water.

The runoff concentrations for sediment (13.8 g L^{-1}), TP (10.1 mg L^{-1}), and DRP (0.47 mg L^{-1}) in untreated Fall-Rototill furrows (Table 3) were two to three times greater than that reported by Lentz and Lehrsch (2010) also for initial irrigations on recently manure-amended, furrow-irrigated Portneuf soils. In addition, runoff NH_4–N concentrations (0.22 mg L^{-1}) for our Fall-Control furrows were 4 to 20 times greater and NO_3–N concentrations (0.08 mg L^{-1}) (Table 3) were 20 to 75% smaller than those of Lentz and Lehrsch (2010). The differences between runoff sediment and nutrient concentrations of the current study and those from the recently manure-amended, furrow-irrigated field of Lentz and Lehrsch (2010) may be due to the discrepancies in erosion rates, manure composition, or the timing of manure application between the two studies. Lentz and Lehrsch (2010) applied manure in late fall and early spring when the stockpiled manure and receiving soil were moist. In the current study, manure was applied in late summer when the manure and soil were dry, and moisture levels remained low up to the time of the fall irrigation; thus conditions in the soil were less conducive to nitrification.

The DRP concentrations in our Fall-Control treatment were 1 to 10 times greater than that from flood-irrigated pastures amended with superphosphate fertilizer that had been drilled 75 mm below the soil surface (Mundy et al., 2003). The DRP concentrations in our Fall-Control furrows, however, were 83 to 97% less than that reported for flood-irrigated pastures amended with surface-broadcast, unincorporated superphosphate fertilizer (Austin et al., 1996; White et al., 2003). The readily accessible and soluble P from the unincorporated superphosphate fertilizer substantially increased DRP transport in runoff relative to drilled-in fertilizer or incorporated manure.

Experiment 2: Spring Tillage and Water-Soluble Polyacrylamide Effects

Tillage treatments applied in spring to soils that were manure amended in the previous fall had little influence on furrow runoff components or cumulative mass losses (Table 3). While mean furrow runoff concentrations from moldboard-plowed soils consistently trended lower for sediment, DOC, DRP, and TP than rototilled soils, these differences were not statistically significant. Plowing did significantly reduce cumulative DRP losses, however, by 58% relative to rototilled soils.

Several factors probably caused runoff mass losses in the Spring-Plow treatment to trend lower than those of the Spring-Rototill treatment:

> 1. Component concentrations trended lower in plowed soils (except possibly for NO_3–N) due to the inversion of manure below the surface, e.g., soil P in plowed plots was 38.2 mg kg^{-1} vs. 73.3 mg kg^{-1} for rototilled plots. Sharpley et al. (1981) determined that soluble P in rainfall-induced runoff water is released from a 3-mm-deep layer of surface soil.
>
> 2. Sediment concentrations trended lower in Spring-Plow vs. Spring-Rototill furrow streams (Table 3).
>
> 3. Runoff volumes in plowed plots trended lower than for rototilled plots.

Because component losses in furrow runoff are positively correlated with soil nutrient concentration, sediment concentration, and runoff volume (Bjorneberg et al., 2006; Lentz and Lehrsch, 2010), all three of these factors would promote lower runoff component losses in plow-treated furrows.

Little et al. (2005) reported that moldboard plowing was more effective than double disking or cultivating for reducing DRP, TP, NO_3–N, and NH_4–N loads in runoff from simulated rainfall events, with moldboard plowing reducing the nutrient losses by 50 to 95% relative to other tillage. In their study, however, the runoff event was scheduled within 5 d of manure application and tillage. This suggests that the benefit of tillage for reducing runoff nutrient losses is greatest when tillage is applied shortly after manure application.

The mean component concentrations and mass losses from Spring-WSPAM furrows were at times considerably smaller than the spring controls, while at other times the differences were not significant (Table 3). Clearly the Spring-WSPAM treatment was not as broadly effective as Fall-WSPAM for improving runoff water quality; however, the significant reductions in sediment, DOC, DRP, and TP runoff mass losses produced by Spring-WSPAM relative to Spring-Control were proportionally similar to that produced by the Fall-WSPAM treatment in the fall 1999 irrigation (Table 3). For example, WSPAM reduced sediment mass losses by 100% in the fall vs. 99% in the spring and decreased TP mass losses by 99% in the fall vs. 98% in the spring.

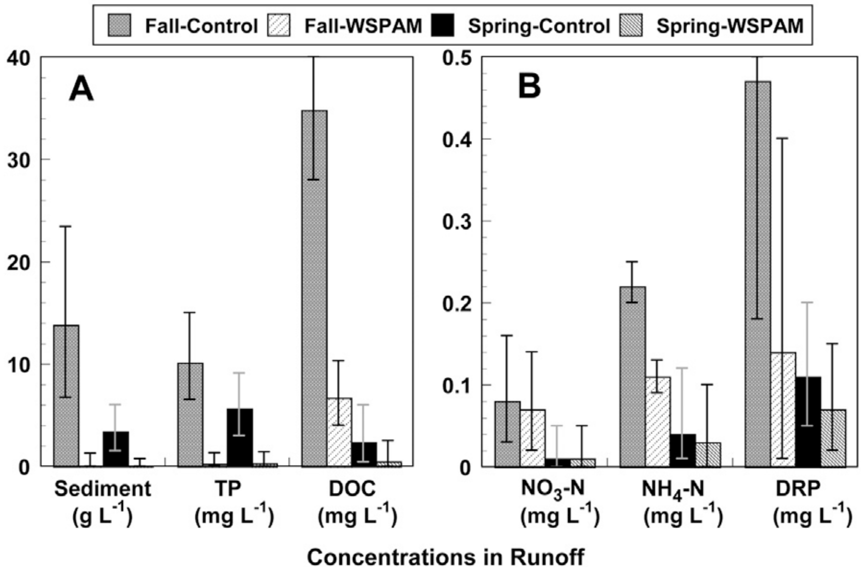

Fig. 1. (A) Mean sediment, total P (TP), and dissolved organic C (DOC) and (B) NO_3–N, NH_4–N, and dissolved reactive P (DRP) concentrations in furrow runoff (Fall-Control, Fall-water-soluble polyacrylamide [WSPAM]) from the fall irrigation on late-summer manure-amended soils (Exp. 1) compared with that from an irrigation on the manure-amended soils (Spring-Control, Spring-WSPAM) that was delayed until the following spring (Exp. 2). All treatments were rototilled. Error bars represent 95% confidence limits on the treatment means.

Experiment 3: Conventional vs. Buried Lateral Systems

Relative to conventional furrows, the buried lateral furrow irrigation system reduced furrow runoff rates by 67% (Table 4), decreased runoff concentrations of sediment by 81%, NH_4–N by 57%, and TP by 69%, and reduced cumulative mass losses of sediment by 89%, DOC by 90%, and TP by 82% (Table 3). In addition, the infiltration fraction for buried lateral furrows was comparable to those of the WSPAM furrows, which consistently trended higher than for the associated control furrows (Table 4). Thus the buried lateral system was an efficient method of irrigation that substantially improved runoff water quality.

The buried lateral treatment improved runoff water quality by minimizing furrow stream sizes, reducing stream velocities and associated shear forces, and limiting runoff volumes (irrigation inflow volumes were similar for both). These, in turn, reduced erosion and sediment transport rates. For example, the buried lateral treatment reduced the mean runoff rates by 67% relative to the untreated furrows, while the Spring-WSPAM treatment reduced the mean runoff by only 43% relative to the untreated furrows (Table 4). The mean runoff rate for the buried lateral furrows was least of all the experimental treatments. Accordingly, the mean total runoff amounts for the buried lateral furrows trended lower than for the conventional furrows. This, combined with lower sediment concentrations, led to the observed decrease in DOC and TP mass losses in the buried lateral furrows relative to the control.

In general, the water quality benefits provided by the buried lateral system appear to be comparable to that provided by WSPAM. An advantage of using the buried lateral approach over that of WSPAM is its ability to irrigate a greater crop area with an equivalent water supply.

Delayed Irrigation Effects

Figures 1 and 2 present results from the control and WSPAM treatments in both fall and spring irrigations to deter-

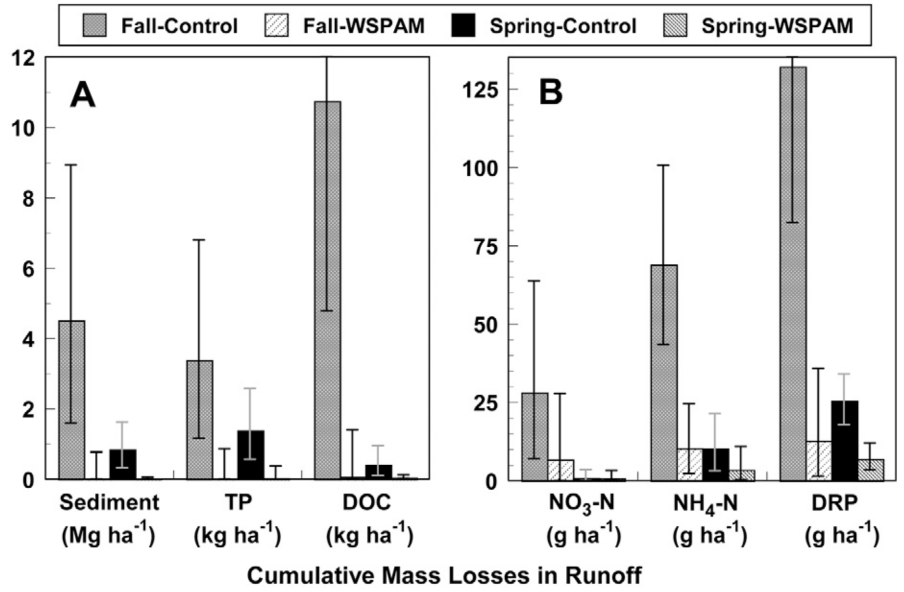

Fig. 2. Cumulative (A) sediment, total P (TP), and dissolved organic C (DOC) and (B) NO_3–N, NH_4–N, and dissolved reactive P (DRP) mass losses in furrow runoff (Fall-Control, Fall-water-soluble polyacrylamide [WSPAM]) from the fall irrigation of late-summer manure-amended soils (Exp. 1) compared with that from an irrigation on the manure-amended soils (Spring-Control, Spring-WSPAM) that was delayed until the following spring (Exp. 2). All treatments were rototilled. Error bars represent 95% confidence limits on the treatment means.

mine whether the irrigation delay produced runoff water quality benefits. Treatment differences were examined using 95% confidence limits computed on treatment mean values. Caution is needed when drawing conclusions comparing treatments between the fall and spring experiments because all treatment experimental units were not distributed across a common field area. Because the experimental plots were adjacent and located on a uniform geomorphic surface, however, we considered that the effect of soil variation between experimental plots was small relative to the treatment effects. Subject to this qualification, the following conclusions may be drawn.

Delaying the first irrigation on the late-summer manure-amended soil from fall to the next spring (Fall-Control vs. Spring-Control) resulted in substantially reduced runoff component concentrations and mass losses, with the exception of TP mass losses. Delayed irrigation in the control furrows decreased the runoff sediment concentration by 75%, DOC 93%, NO_3–N 88%, NH4-N 82%, and DRP 77% relative to the fall irrigation (Fig. 1). Because the fall and spring irrigations did not differ with respect to total irrigation inflows, runoff, or net infiltration (Fig. 3), the reduced runoff nutrient mass losses resulted primarily from decreased nutrient concentrations in the furrow stream. This in turn was at least partly due to the dramatically reduced sediment concentrations in the spring furrow streams relative to those in the fall (Fig. 1).

Clearly, the fall soils were more susceptible to erosion than the spring soils. We attribute this to the dry soil conditions that prevailed in the fall compared with the spring. Between the manure application in August and the first irrigation, the fall soils had received only 1 mm of precipitation, while in spring, the soils were moist from winter rains (Table 1), including 27.2 mm of precipitation that occurred in the 3 wk before the first irrigation. Increasing the water content of these soils from 5 to 10% (kg kg^{-1}) can increase soil aggregate stability twofold under the rapid wetting conditions that occur when a furrow irrigation is initiated (Kemper et al., 1985).

Reduced spring furrow stream nutrient concentrations probably also reflect the reduced concentrations of nutrients in the surface soil at the time of irrigation, which resulted from volatilization, leaching, and mineralization–immobilization processes acting on the manure between the time of its application and the first irrigation. The 163.6 mm of precipitation that fell on the spring soils during the period between manure application and the first irrigation (Table 1) undoubtedly influenced the chemical characteristics of the surface soil. Leaching probably removed soluble nutrients such as NO_3–N and NH_4–N from the surface soils, making the nutrients less available for transport in runoff.

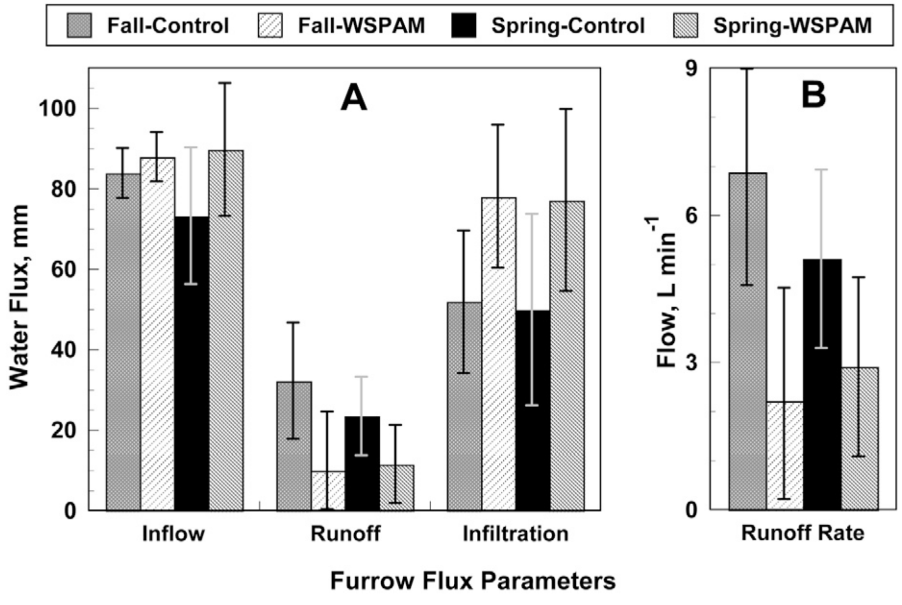

Fig. 3. (A) Cumulative irrigation inflow, runoff, and infiltration and (B) mean runoff rate for furrows (Fall-Control, Fall-water-soluble polyacrylamide [WSPAM]) from the fall irrigation of late-summer manure-amended soils (Exp. 1) compared with that from an irrigation on the manure-amended soils (Spring-Control, Spring-WSPAM) that was delayed until the following spring (Exp. 2). All treatments were rototilled. Error bars represent 95% confidence limits on the treatment means.

Smith et al. (2007) and Gilley et al. (2007) observed similar decreases in runoff soluble P and NH_4–N concentrations with time after application of unincorporated swine or cattle manure under rainfall; however, Smith et al. (2007) reported that runoff NO_3–N concentrations increased with time after manure application, presumably due to the accumulation of mineralized NO_3. As in this study, Gilley et al. (2007) did not observe a significant reduction in runoff TP concentration 11 mo after cattle manure application. Average runoff DRP and inorganic N concentrations reported by Gilley et al. (2007) for rainfall events 30 d after manure application were at least three to four times greater than observed here. This was partly because their runoff events were of short duration relative to furrow irrigations (30 min vs. 24 h). Inorganic N and P concentrations in irrigation furrow runoff typically are greatest early in the irrigation and decline with time (Lentz and Lehrsch, 2010).

Reductions in runoff component mass losses were also sizeable when irrigation was delayed until spring: sediment 81%, DOC 96%, NO_3–N 97%, NH_4–N 85%, and DRP 80% (Fig. 2). While the mean TP mass loss value for the Fall-Control rototilled irrigation (3381 g ha^{-1}) was greater than its associated Spring-Control rototilled loss (1378 g ha^{-1}), the difference was not significant. The nutrient losses observed for TP, DRP, and NH_4–N in our study were comparable to the rainfall-induced losses observed by Miller et al. (2006) when they subjected fall-manured fields to spring rainfall amounts that were roughly similar to that applied in our furrow irrigations.

CONCLUSIONS

This study conducted in semiarid southern Idaho monitored the first furrow irrigation on soil amended in late summer with stockpiled dairy manure. We determined the effects of WSPAM, tillage, conventional vs. buried lateral furrow irrigation, and delayed irrigation on runoff water quality. The four management approaches effectively decreased the runoff volume and the concentrations or cumulative mass losses for one or more furrow stream components: sediment, TP, DOC, NO_3–N, NH_4–N, and DRP.

The use of WSPAM as a management tool is attractive because it effectively controlled runoff sediment and nutrient losses and did not require a large initial capital outlay as did the buried lateral system. It also can be selectively applied to individual irrigations depending on need. For example, irrigations late in the season may not need to be treated because potential nutrient losses in these furrow irrigations are relatively small (Lentz and Lehrsch, 2010). The buried lateral system was slightly less effective than WSPAM for controlling runoff nutrient losses and was more costly up front. With proper management, however, these systems are capable of attaining water application efficiencies of 90 to 95% (Worstell, 1976). The long-term benefits of buried lateral systems may include water savings as well as increased runoff water quality. Note that the cost associated with these management practices may be partially offset by a reduction in replacement fertilizer expenses (Lentz and Lehrsch, 2010).

Sediment and nutrient runoff losses can be substantially reduced by applying manure in the fall and delaying irrigation until spring. Combining the irrigation delay with moldboard plowing, WSPAM, or buried lateral irrigation, however, can provide sizeable further reductions in runoff component concentrations and cumulative losses. The use of moldboard plowing in spring, in addition to irrigation delay, provided the least additional benefit. Results from this study and those in the literature suggest that the greatest benefit from moldboard plowing may accrue when the field is plowed soon after the manure is applied, whether or not the irrigation is delayed.

Although amending surface-irrigated soils with manure generally increases the potential for nutrient loss in runoff, the results from this research demonstrate that several types of management approaches may be successfully used to substantially reduce the offsite nutrient transport associated with furrow irrigation.

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