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Erosion control practices integrated with polyacrylamide for nutrient reduction in rill irrigation runoff

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ARTICLE INFO

Article history:
Accepted 9 April 2007
Published on line 16 May 2007

Keywords:
Furrow irrigation
Rill irrigation
Polyacrylamide
Erosion control
Sediment
Nutrients
Nitrogen
Nitrate
Phosphorus
Soluble phosphorus

ABSTRACT

The objective of this research was to assess soil conservation practices for improving water quality of return flows from rill irrigation in the Yakima River Basin, Washington, by combining patch application of polyacrylamide (PAM) with an additional erosion control practice. A 2-year field study was conducted that combined PAM with (1) check dams, (2) surge irrigation, (3) surface drains, and (4) grass filter strips. The study was conducted at three sites: two vineyards (A and B) with silt loam soils at 1.2% slope and a cornfield with sandy loam soils at 0.2% slope. During irrigation events, water samples and flow records were taken at periodic intervals from each treatment to determine nutrient concentrations and loads (total nitrogen (TN), total Kjeldahl N (TKN), nitrate–N (NO_3–N), total phosphorus (TP), particulate P (PP), soluble phosphorus (SP), and sediment load (SL)). For all treatments and sites, TN and TP concentrations were compared to USEPA value concentrations in streams of the Xeric West for full support of aquatic life and drinking water standards. Results showed that TN exceeded the USEPA-reference condition of 0.36 mg TN/L in all samples, while 96% of the samples exceeded the USEPA-recommended TP concentration value of 0.1 mg/L. All samples showed NO_3–N concentrations below the USEPA drinking-water standard of 10 mg/L. The only nutrient component in irrigation runoff that was strongly related to SL was PP concentration ($r = 0.87$). For TKN, significant concentration and load reduction between control and the other four erosion control practices ($P < 0.05$) occurred only in vineyard A. As for PP, the four PAM integrated control practices showed statistically significant effects with respect to the PAM control in vineyard B only. Although PAM is an excellent practice to control soil erosion with widespread adoption, additional off-site treatment may be needed for nutrient concentrations in irrigation return flows to meet reference conditions that would fully support aquatic life.

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1. Introduction

Application of polyacrylamide (PAM) is an economical practice that has been rapidly adopted in the Yakima River Basin, Washington to substantially reduce soil erosion in rill irrigation and improve water quality in irrigation return flows (Fuhrer et al., 2004). Several studies showed that PAM application simultaneously reduced sediment and plant nutrient losses in irrigation runoff (Entry and Sojka, 2003; Lentz et al., 1998a). Yet, several Yakima River tributaries need

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0378-3774/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.agwat.2007.04.003

to meet the regulatory sediment concentration standard (total maximum daily load or TMDL) and should have nutrient levels below recommended guidelines. Thus, additional erosion control practices combined with PAM application may be necessary to effectively reduce both sediment and nutrient concentration in irrigation return flows to environmentally safe levels.

Polyacrylamide (PAM) is widely used in the food industry, mineral processing, and municipal water treatment as a settling agent (Barvenik, 1994). It also has being extensively used in furrow irrigation for soil erosion control and increased infiltration (Lentz et al., 1992; Lentz and Sojka, 1994; Sojka et al., 1998a, 1998b). Polyacrylamide is a stable compound and considered to be environmentally safe for use as a soil conditioner (Bologna et al., 1999; Seybold, 1994). Most studies have shown that when PAM was correctly used, there was a 48–90% reduction in sediment exiting the furrows (Zhang and Miller, 1996). In addition, it has been shown that PAM application has the benefit of both reducing microbial (Entry et al., 2002) and weed seed transfers in runoff (Sojka et al., 2003). With respect to nutrient concentration in water runoff, PAM treatments could reduce nitrate concentration from zero up to 85% and total phosphorus concentration by 90% in water compared to runoff water in furrows without PAM (Lentz et al., 1998a,b; Entry and Sojka, 2003).

In a two-season and multiple-site study, Leib et al. (2005) assessed the effect of additional erosion control practices integrated with PAM to meet the sediment TMDL standard for irrigation return flows to the Lower Yakima River. They evaluated four rill irrigation conservation practices in combination with PAM application: (1) surge irrigation, (2) grass filter strips, (3) check dams, and (4) surface drains. They then compared sediment yields of these four treatments to sediment yields from rill irrigation control plots treated with PAM alone. Their study showed that the PAM control plots dramatically reduced soil erosion. Yet, PAM control plots yielded sediment concentrations greater than the Yakima River TMDL standard (56 mg/L). Only the grass filter strip with PAM treatment was effective to reduce sediment concentrations below the TMDL standard. Runoff water samples from their study were also analyzed for nutrient content (nitrogen and phosphorus), but not included in their report. The objectives of the present study were to examine the nutrient concentration data related to the four soil erosion control practices combined with PAM technology used by Leib et al. (2005) to determine their efficacy to reduce both nutrient concentrations and nutrient loads in irrigation runoff with respect to a PAM-alone control treatment.

2. Materials and methods

2.1. Description of sites

Three rill irrigated farm sites, two vineyards, and one grain cornfield were used in this study. All sites were located in Washington State in a semi-arid environment with 177 days of growing season and an average annual normal precipitation of 202 mm (U.S. Bureau of Reclamation, 2006). This precipitation during the growing season is not a significant contribution to the total crop–water use in any of the three sites. Vineyard A located north of Prosser, WA (119.8°W 46.3°N) in the Roza Irrigation District, was used during the 2001 crop season. Vineyard A consisted of a 10-year-old 'Concord' grape (*Vitis lambruscana* L.) with a surface area of 12 ha and a slope of 1.2% in both the furrows and the ditch. The predominant soil was a Shano silt loam (coarse-silty, mixed, superactive, mesic Xeric Haplocambid) (USDA-SCS, 1985). Vineyard B, located 10 km east of Vineyard A, was used during the 2002 crop season. The grape type, soil, slope, and surface area at this site were similar to those at Vineyard A. The cornfield, used for both 2001 and 2002 corn (*Zea mays* L.) crop seasons, was located in the Wapato Irrigation District near Mabton, WA (120.1°W 46.1°N). The dominant soils for this site were Warden very fine sandy loam (coarse-silty, mixed, superactive, mesic Xeric Haplocambids) on the northwestern half of the field and Esquatzel fine sandy loam (coarse-silty, mixed, superactive, mesic Torrifluventic Haploxerolls) on the southeastern half of the field (USDA-SCS, 1976). The field had a surface area of 16 ha with an average slope of 0.2% in both the furrows and tailwater ditch.

2.2. Treatment layout and irrigation events

Crop management, irrigation scheduling and PAM application at each study site were handled by the individual growers. Granular anionic PAM was applied at all sites by the patch method; dry PAM was poured directly into individual furrows (Leib et al., 2005). At both vineyards, one tablespoon or about 100 g of PAM was applied 1 m downhill from the irrigation hose in each furrow approximately 15 min after the start of irrigation. A rate of 1.1 kg PAM ha^{-1} (or about 10 mg L^{-1}) during advance is the recommended practice (NRCS, 2001). At vineyard B, a second patch application of PAM was used at the top of the furrows about 24 h after the start of the irrigation event with vineyard irrigation events lasting 48 h. In the cornfield, irrigation events lasted 24 h and 100 g of PAM was patch-applied to dry furrows. Five erosion control practices were integrated to PAM applications in five field treatments: (1) only PAM addition to the furrow (control); (2) PAM addition plus check dam; (3) PAM plus surge irrigation; (4) PAM plus surface drains; and (5) PAM plus grass filter strip. Check dam structures were made of 13-mm-thick plywood. Four dams were installed at the vineyards and two at the cornfield so that ponded water would back up to the next check structure during an irrigation event. Surge irrigation at vineyard A was done manually by turning spigot valves on and off. Eight out of sixteen furrows per treatment were irrigated and switched back and forth every 2–3 h. At vineyard B and the cornfield, an automatic surge valve was installed with star controller (P & R Company, Lubbock, TX). The controller advance time was set for 4 h at vineyard B and 9 h at the cornfield. Surface drains consisted of polyvinyl chloride (PVC) pipe (0.065-m diameter at the vineyards and 0.1-m diameter at the cornfield) buried at 0.15-m depth underneath the tailwater ditch. Riser pipe was connected to the buried pipe at a 12-m interval in the vineyards and at a 15-m interval in the cornfield. The inlet of the riser pipe was located about 30 mm above the ditch bottom, and a low soil dam was placed downstream of the inlet to ensure that water would not bypass the inlet. For the

Table 1 – Date and field conditions of monitored rill irrigation events in 2001 and 2002 for vineyards and cornfield sites

Site	Year	Observation days	Furrow condition[a]	Wheel track[b]
Vineyard A	2001	June 12–14	Dry	None
Vineyard A	2001	July 22–24	Wet	None
Vineyard A	2001	August 13–15	Wet	None
Vineyard B	2002	June 11–13	Dry	None
Vineyard B	2002	July 1–3	Wet	All
Vineyard B	2002	July 9–10	Wet	None
Vineyard B	2002	July 28–30	Dry	All
Vineyard B	2002	August 7–9	Wet	All
Vineyard B	2002	August 19–21	Wet	None
Cornfield	2001	July 16–18	Dry	None
Cornfield	2001	July 28–30	Wet	None
Cornfield	2002	June 22–27	Dry	2/3s
Cornfield	2002	July 12–13	Dry	None
Cornfield	2002	July 23–25	Wet	2/3s
Cornfield	2002	July 31–August 2	Wet	None

[a] Dry means either furrows that have been newly formed and are being irrigated for the first time or existing furrows that have been re-formed and are being irrigated for the first time since being re-formed; wet means furrows that have been previously irrigated.
[b] Indicates the estimated proportion of furrows in an irrigation event that were compacted by tractor traffic.

grass filter strip, as soon as the tailwater ditch was excavated, Kentucky Bluegrass sod (*Poa pratensis* L.) was planted and irrigated for about 2–3 weeks to establish the filter strip. At the time when irrigation events started, the grass was healthy and well established. Fertilization for the vineyards and cornfield was performed according to Washington State University Extension guidelines FG-13 (Dow et al., 1979) and FG-6 (Dow et al., 1983), respectively. Nitrogen was incorporated into soil via light discing in late winter as ammonium nitrate (NH_4NO_3) at a rate of about 70 kg/ha for vineyard A and 60 kg/ha for vineyard B. For the cornfield, N was applied as NH_4NO_3 by incorporating into the soil before planting at a rate of 150 and 200 kg/ha in 2001 and 2002, respectively. Maintenance P applications (80 kg P_2O_5/ha) as triple superphosphate were made during fall according to soil test recommendations. Further description of treatment layouts and irrigation events using PAM and integrated erosion control practices are found in Leib et al. (2005).

Each vineyard was irrigated 10 times. Three irrigations events were monitored in vineyard A, while six irrigation events were monitored in vineyard B (Table 1). Sometimes, the furrows had the addition of wheel traffic from spray operations (Table 1). Also, the furrows in vineyard B were re-formed midway through the growing season.

In 2001 and 2002, the cornfield was irrigated six times and nine times, respectively. Two irrigation events were monitored in 2001 and four were monitored in 2002 (Table 1). Wheel traffic was always kept in the same alley between cornrows both before and after furrow formation so that some of the monitored events contained wheel track furrows.

2.3. *Flow monitoring and sediment load*

Runoff flow was collected in a sump that consisted of an elliptical 1.2-m-long, 0.6-m-wide, and 0.6-m-deep plastic trough (Leib et al., 2005). An inlet pipe placed on the same level as the tailwater ditch allowed water to free fall onto a wire mesh screen used to remove large debris before water reached the bottom of the sump. A float-activated sump pump (Teel Model 3P546F, Niles, IL) with a 373 W motor and maximum outflow of 390 L min^{-1} at 1.5 m head was placed in the sump. The pump moved water through a 0.08-m-diameter flow meter with a totalizer (McCrometer, Hemet, CA), and then released water into a slotted plastic bin (1.2 m × 1.2 m × 0.6 m) that was lined with filter fabric (No. 6, DeWitt Co., Sikeston, MO). After water passed through the plastic bin, it was routed to avoid mixing runoff water from adjacent plots. Mean irrigation runoff per treatment in vineyard and cornfield sites is shown in Fig. 1.

Water samples were collected by hand in 250 mL bottles at the inlet pipe as runoff fell into the sump. For every treatment, the normal protocol was for samples to be collected by sampling the runoff every hour for approximately the first third of the runoff period, every 2 h for the middle third, and every 3 h for the last third of the runoff period and composited into one sample per irrigation event. Water samples were

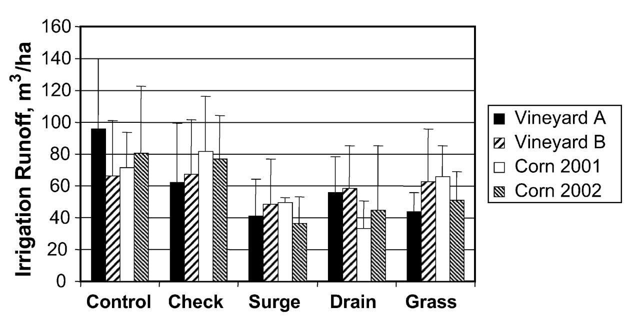

Fig. 1 – Mean irrigation runoff per treatment in vineyards and cornfield sites (2001–2002). The control is polyacrylamide-alone (PAM) application; the other four treatments are a combination of a conservation practice plus PAM application. Error bars represent one standard deviation. Data from Leib et al. (2005).

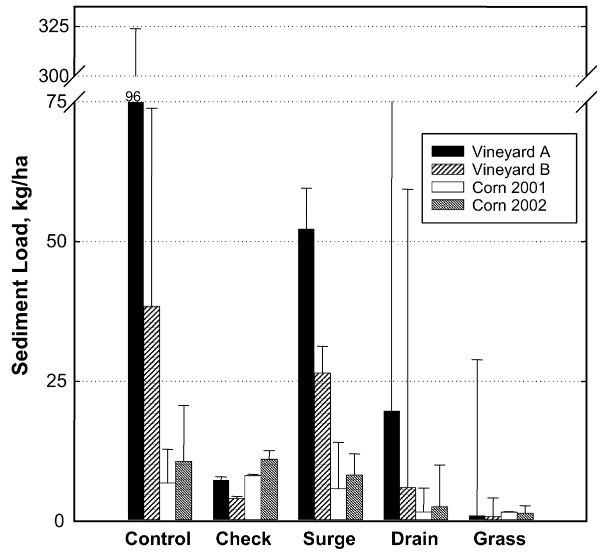

Fig. 2 – Mean sediment load in irrigation runoff per treatment in vineyards and cornfield sites (2001–2002). The control is polyacrylamide-alone (PAM) application; the other four treatments are a combination of a conservation practice plus PAM application. Error bars represent one standard deviation. Data from Leib et al. (2005).

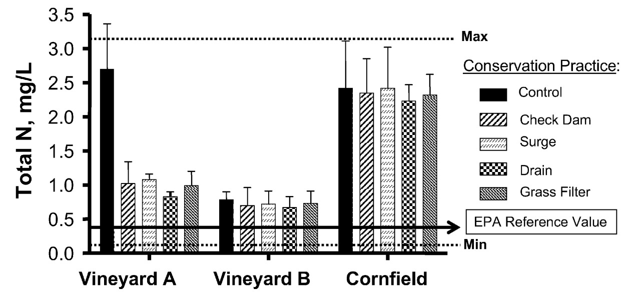

Fig. 3 – Mean total nitrogen concentration in runoff from rill irrigation at three study sites with a control with PAM-alone application and four conservation practices combined with polyacrylamide (PAM) application (check dams, surge irrigation, drain, and grass filter). The error bars represent one standard deviation. The horizontal dashed lines represent maximum and minimum total nitrogen concentrations reported by EPA for Columbia Plateau Ecoregion 10 (within Aggregate Ecoregion III). The full line represents the EPA Reference Condition value to protect aquatic resource quality in rivers and streams in Ecoregion 10 (USEPA, 2000).

chilled during transportation and placed in cold storage (<4 °C) until analysis. Sediment analysis for water samples were described and results reported by Leib et al. (2005); mean and standard deviation of sediment load in irrigation runoff per treatment in the vineyards and cornfield are shown in Fig. 2.

2.4. Water analyses

Water samples were analyzed for total Kjeldahl nitrogen (TKN), nitrite plus nitrate–N, total phosphorus (TP), and orthophosphate–P using EPA methods: 351.2, 353.2, 365.2, and 365.1, respectively (U.S. EPA, 1983). All N and P analyses were performed using an automated analyzer (Alpkem-OI Corp., College Station, TX). Since nitrite–N was negligible, the nitrite plus nitrate–N is called nitrate–N (NO_3–N) hereafter. The TKN analysis included ammonium–N fraction, and total N (TN) was considered as the sum of TKN plus NO_3–N. The orthophosphate–P fraction that represents soluble reactive P (SP) was determined after filtration through a 0.45 μm membrane filter (Gelman type Supor-450, Pall Corp., Ann Arbor, MI). The difference between TP and SP was considered the solid P fraction (including organic, low solubility inorganic, or adsorbed P forms) and called particulate phosphorus (PP) (Newton and Jarrell, 1999). Nutrient mass load loss per unit area was calculated from the TKN, NO_3–N, TP, PP, and SP concentration values, total cumulative flow per irrigation event, and the plot area. Each irrigation event for a given field was considered as replications for statistical analysis. The general linear model (GLM) procedure of the SAS Institute (2000) was used for repeated measures analyses of variance, mean separation by Duncan test, and regression analyses.

3. Results and discussion

3.1. Nutrient concentrations

Total N concentrations in all treatments and sites were compared to USEPA reference TN concentrations in streams of the Xeric West for full support of aquatic life (Aggregate Nutrient Ecoregion III; USEPA, 2000). This USEPA reference condition, based on the 25th percentile of reported nutrient concentration values for an ecoregion, provides a starting upper point for states and tribes in the development of their own criteria. The Yakima River Basin is part of the Columbia Plateau Ecoregion 10 (within Aggregate Ecoregion III) with an EPA reference condition maximum value of 0.36 mg TN/L. Results from our study show that all samples of runoff irrigation exceeded the EPA reference value for TN. However, except for the PAM control in vineyard A, all conservation practices were below the maximum TN of 3.083 mg TN/L reported (observed) for Ecoregion 10 (Fig. 3).

In a special study of small agricultural watersheds in the Yakima River Basin with widespread use of PAM alone as the soil erosion control practice in fields with rill irrigation, concentrations of TP in 71% of the samples during the irrigation season exceeded the USEPA (1986) TP maximum value of 0.1 mg/L to prevent undesirable growth of plants in streams (Ebbert et al., 2003; Fuhrer et al., 2004). Our results are consistent with the small agricultural watershed study since 96% of our samples exceeded the USEPA's TP value of 0.1 mg/L in all three sites and treatments (Fig. 4). According to Leib et al. (2005), the grass filter strip with PAM treatment was the only treatment that reduced sediment below TMDL values, but our study shows that this practice was ineffective to control TP below the USEPA-recommended value of 0.1 mg/L.

Soluble and particulate forms of nutrients and their concentrations were further considered to better understand the performance of erosion control practices of our study. The

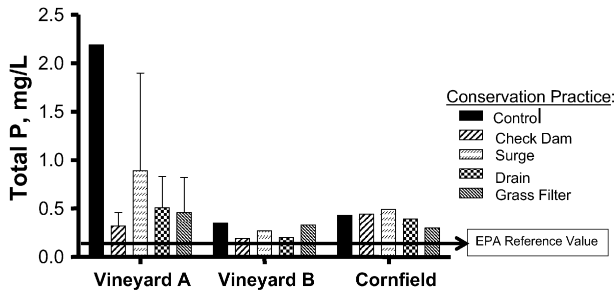

Fig. 4 – Mean total phosphorus concentration in runoff from rill irrigation at three study sites with a control with PAM-alone application and four conservation practices combined with polyacrylamide (PAM) application (check dams, surge irrigation, drain, and grass filter). The error bars represent one standard deviation. The horizontal full line represents the EPA reference maximum value of 0.1 mg/L for limiting undesirable plant growth in streams (USEPA, 1986).

National Water Quality Assessment (NAWQA) Program study conducted by the U.S. Geological Survey in streams and drains of the Yakima River Basin found that NO_3–N and SP were the dominant forms of N and P, respectively (Fuhrer et al., 2004). These forms of N and P are highly soluble, and inputs to fresh waters can accelerate eutrophication (Sharpley et al., 2000). Our results showed that TKN was the dominant form of N in the runoff water of all conservation practices in both vineyards A and B (Table 2). Overall, concentration of TKN in irrigation runoff was higher in vineyard A than in vineyard B or cornfield. In particular, average TKN concentration was highest in the control treatment of vineyard A and statistically different ($P < 0.05$) from the mean TKN concentration in irrigation runoff of the other four integrated conservation practices. For the cornfield, the dominant N form in irrigation runoff was NO_3–N for all conservation treatments (Table 2). The pooled average of all conservation treatments was highest for the NO_3–N concentration in runoff for the cornfield (1.94 mg/L) and significantly different ($P < 0.005$) for both vineyards A (0.09 mg/L) and B (0.16 mg/L). Important to notice is that single application of N fertilizer at the beginning of the crop season did not greatly influence NO_3–N concentrations in runoff of successive irrigation events. There were no significant differences in NO_3–N concentration among irrigation runoff for single events for any treatment in both vineyards. For the cornfield, only in 2002, there was an average decrease (all treatments pooled) in NO_3–N concentration in irrigation runoff by about 20% between the first and fourth irrigation. With respect to the NO_3–N drinking water standard, the concentrations of NO_3–N in water samples for all erosion control practices in both vineyards and cornfield sites did not exceed the USEPA drinking water standard of 10 mg/L (USEPA, 2004).

With respect to P, our results showed that for all four erosion control practices and the PAM control, in all three sites, PP was the dominant form of P (Table 2). Since P is usually tightly sorbed to sediment particles, soil erosion determines PP movement (Sharpley et al., 1993). As both PP and SP move with runoff, there is a progressive decrease in PP

Table 2 – Nutrient concentrations in runoff from rill irrigation using polyacrylamide and integrated soil conservation practices

Practice	Nutrient concentration (mg/L)					
	Total N	Total Kjeldahl N	Nitrite N	Total P	Particulate P	Soluble P
Vineyard A						
Control*	2.70 (0.66) a**	2.60 (0.70) a	0.10 (0.03) a	2.19 (2.20)	2.10 (2.27)	0.09 (0.09)
Check	1.01 (0.32) b	0.90 (0.28) b	0.11 (0.03) a	0.33 (0.14)	0.26 (0.14)	0.07 (0.06)
Surge	1.07 (0.08) b	0.95 (0.07) b	0.12 (0.01) a	0.89 (1.02)	0.80 (1.09)	0.09 (0.09)
Drain	0.83 (0.07) b	0.75 (0.07) b	0.08 (0.1) ab	0.51 (0.32)	0.44 (0.37)	0.07 (0.06)
Grass	1.16 (0.21) b	0.95 (0.21) b	0.04 (0.01) b	0.43 (0.36)	0.16 (0.02)	0.27 (0.35)
Probability > F***	0.011	0.015	0.032	0.288	0.287	0.599
Vineyard B						
Control	0.79 (0.11)	0.64 (0.11)	0.15 (0.07)	0.35 (0.14)	0.24 (0.14) a	0.11 (0.04) a
Check	0.70 (0.20)	0.55 (0.22)	0.15 (0.10)	0.19 (0.03)	0.07 (0.03) b	0.12 (0.06) a
Surge	0.72 (0.19)	0.55 (0.20)	0.17 (0.10)	0.27 (0.12)	0.17 (0.12) ab	0.10 (0.04) a
Drain	0.67 (0.16)	0.48 (0.17)	0.19 (0.08)	0.20 (0.04)	0.08 (0.04) b	0.12 (0.04) a
Grass	0.73 (0.18)	0.57 (0.12)	0.16 (0.14)	0.33 (0.05)	0.09 (0.05) b	0.24 (0.16) b
Probability > F	0.856	0.616	0.952	0.133	0.012	0.032
Cornfield						
Control	2.74 (0.31)	0.60 (0.31)	2.14 (1.10)	0.30 (0.26)	0.16 (0.17)	0.14 (0.09)
Check	2.45 (0.21)	0.58 (0.21)	1.87 (0.44)	0.44 (0.38)	0.36 (0.38)	0.08 (0.02)
Surge	2.54 (0.28)	0.73 (0.28)	1.81 (0.47)	0.49 (0.40)	0.39 (0.36)	0.10 (0.04)
Drain	2.38 (0.26)	0.57 (0.26)	1.81 (0.55)	0.25 (0.13)	0.17 (0.14)	0.08 (0.01)
Grass	2.66 (0.31)	0.61 (0.31)	2.05 (1.10)	0.43 (0.37)	0.34 (0.37)	0.09 (0.02)
Probability > F	0.982	0.893	0.800	0.656	0.510	0.234

* Control is polyacrylamide-alone (PAM) application.
** In a same column within a site, means followed by a common letter are statistically similar by Duncan test ($P < 0.050$).
*** Probability indicating that there is no significant difference among treatments when values are >0.050.

load by water dilution and sediment deposition, and SP becomes the dominant P form as shown in the NAWQA study (Fuhrer et al., 2004). Unlike the NAWQA study, our water samples contained higher concentration of PP than SP probably because our sampling sites were adjacent to the sediment source (runoff water exiting rill irrigation fields) while most NAWQA sampling sites were located further downstream from rill irrigation fields.

3.2. Nutrient–sediment relationship

The lack of substantial reduction of TN concentration in irrigation runoff for the four integrated conservation practices with respect to PAM control treatment was probably due to the poor association of soluble N forms such as NO_3–N with sediment particles (Lentz et al., 1998b). Thus, TN concentration in runoff was not related to sediment load (SL) when SL was used as single independent variable ($r = 0.02$, Fig. 5A). In the same manner, NO_3–N was not related to SL ($r = 0.20$). However, TKN had a weak linear association to sediment ($r = 0.35$, $P < 0.01$). Since TKN includes both organic N and ammonium N fractions, it is possible that any of these two forms were attached or adsorbed to sediment particles.

For P, it was shown that PAM applied to irrigation water can effectively reduce both sediment and PP, but it was not effective

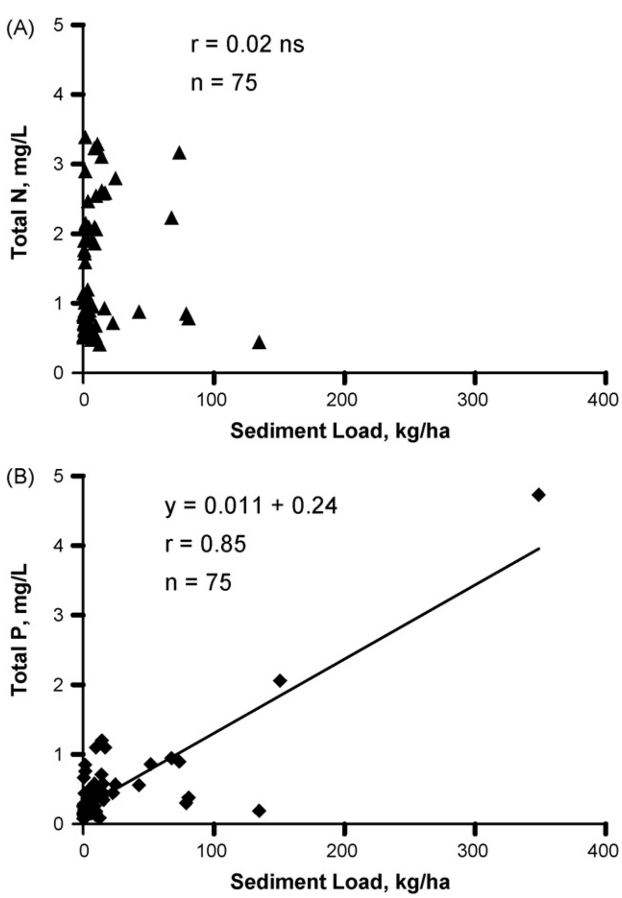

Fig. 5 – Relationship of sediment load vs. total nutrient concentration (pooled by site and conservation practices). (A) Total nitrogen (N), and (B) total phosphorus (P); ns indicates non-significant regression coefficient.

to reduce SP in irrigation runoff (Goodson et al., 2006). We found in our study that SL was a good predictor of TP concentrations in irrigation runoff across sites and treatments ($r = 0.85$, Fig. 5B). Thus, TP concentrations had a significant linear response ($P < 0.01$) to increasing sediment loads in irrigation runoff. Additional regression analyses confirmed that SP was not related to SL ($r = 0.21$), but PP had a significant statistical linear relationship with SL ($r = 0.87$, $PP = 0.11 \times SL + 0.01$, $n = 75$, $P < 0.01$). From this last relationship, we concluded that all four integrated conservation practices had, to a certain degree, simultaneous reduction of sediment load and PP concentrations in irrigation runoff.

3.3. Nutrient mass load

Sediment and nutrient loads gave additional information on how much mass was exported in runoff per unit of irrigated surface. For instance, the control plot in both vineyards A and B had the highest SL (Fig. 2). The check dam, surge, and drain practices gave SL values that were significantly lower than the control, significantly higher than the grass treatment, but statistically similar with each other (Leib et al., 2005). These clear differences among treatments in SL reductions were less significant for different N and P forms. The control plot in vineyard A had the highest mean TKN (193 mg/ha) and PP (247 mg/ha) nutrient load (Table 3). However, significant differences ($P < 0.05$) occurred only in vineyard A for TKN loads between control and the other four erosion control practices. There were no significant differences among control, check dam, surge, drain, and grass filter treatment for both vineyard B and cornfield (Table 3).

Nitrate loads were highest in runoff from the cornfield and significantly different from vineyard A and B. These differences among sites are due to the necessary and consistently higher N fertilizer application rates in the cornfield (150–200 kg N/ha) than N rates usually applied in vineyards (<75 kg/ha) (Davenport et al., 2003). However, mean nitrate loads in runoff were statistically similar for the control, check dam, surge, drain, and grass filter treatments within sites. This indicated that none of the four integrated erosion control practices were superior to the PAM control treatment in reducing nitrate loads within sites.

None of the four integrated erosion control practices were superior to the PAM control treatment in reducing SP loads in irrigation runoff (Table 3). Important to note is that the grass filter treatment with PAM in vineyard B yielded the highest SP load (13 mg/L); this result could be related to release of SP from fertilizer applied to the grass filter strip prior to the start of the field trials.

As for PP, the four PAM integrated control practices in vineyard B showed statistically significant effects with respect to the PAM control on PP loads in runoff (Table 3); PP loads in runoff water increased in the following order: check < drain < grass < surge < control. Although differences among integrated practices and PAM control were not significant for vineyard A and cornfield sites, the grass filter practice showed the smallest range of PP loads (6–9 mg P/ha) in irrigation runoff across the three sites. This trend is consistent with both the results of Leib et al. (2005) that the grass filter treatment with PAM was the most consistent practice to reduce sediments

Table 3 – Nutrient loads in runoff from rill irrigation using polyacrylamide and integrated soil conservation practices

Practice	Nutrient load (mg/ha)					
	Total N	Total Kjeldahl N	Nitrite N	Total P	Particulate P	Soluble P
Vineyard A						
Control*	204 (85) a**	193 (76) a	11 (7)	247 (299)	241 (303)	6 (4)
Check	43 (2) b	36 (4) b	7 (3)	20 (15)	17 (16)	3 (2)
Surge	32 (27) b	27 (14) b	5 (2)	51 (74)	48 (76)	3 (2)
Drain	37 (2) b	32 (1) b	5 (4)	33 (33)	30 (35)	3 (2)
Grass	37 (7) b	35 (7) b	2 (1)	17 (11)	7 (2)	10 (13)
Probability > F***	0.025	0.025	0.129	0.275	0.289	0.578
Vineyard B						
Control	53 (27)	44 (26)	9 (5)	25 (17)	19 (2) a	6 (3) a
Check	41 (10)	33 (12)	8 (4)	11 (3)	4 (2) b	7 (2) a
Surge	36 (27)	29 (25)	7 (3)	14 (13)	10 (12) ab	4 (2) a
Drain	40 (19)	30 (18)	10 (3)	11 (5)	5 (4) b	6 (2) a
Grass	41 (14)	34 (15)	7 (4)	19 (12)	6 (4) b	13 (9) b
Probability > F	0.700	0.714	0.736	0.189	0.049	0.029
Cornfield						
Control	192 (72)	41 (17)	151 (58)	26 (15)	19 (16)	7 (2)
Check	193 (83)	47 (20)	146 (59)	34 (28)	28 (27)	6 (2)
Surge	107 (55)	31 (20)	76 (38)	23 (23)	18 (21)	5 (2)
Drain	96 (75)	29 (42)	67 (39)	9 (5)	5 (3)	4 (3)
Grass	133 (48)	33 (17)	130 (106)	16 (14)	9 (9)	7 (4)
Probability > F	0.059	0.767	0.093	0.224	0.200	0.260

* Control is polyacrylamide-alone (PAM) application.
** In a same column within a site, means (standard deviation) followed by a common letter are statistically similar by Duncan test ($P < 0.050$).
*** Probability indicating that there is no significant difference among treatments when values are >0.050.

below TMDL values and the significant linear relationship between SL and PP concentration in irrigation runoff ($r = 0.87$) discussed in the previous section. These results may be influenced by the PAM application procedures. It is conceivable that differences in protocol could have certain degree of influence on soluble P loss. In the patch method, as specified by NRCS (2001), PAM should be placed on the dry furrow before water enters the furrow. This may have the maximum effect on reducing erosion and maintaining infiltration in the furrow since part of the soluble loss is the result of both mixing of detached sediment and total runoff. Hence, both sediment and runoff are reduced when the patch is applied to the dry soil rather than adding to an established flow. Although not recommended, we included in this study the patch added after water enters the furrow because it is a practice that has been frequently observed in vineyards of the Yakima Valley. Nevertheless, a second PAM application in vineyard B used at the top of the furrow about 24 h after beginning irrigation may have contributed to explain the significant reduction of PP loads.

Since the integrated erosion control practices tested in this study did not reduce soluble nutrient losses in rill irrigation runoff, other potential integrated management practices could be assessed to control soluble nutrients in runoff. These other management practices should help to enhance the combined effect of PAM on both increased infiltration rate and reduction of contact between water and detached sediment. To compensate for PAM application changes in infiltration, inflow management can minimize the amount of runoff water and soluble nutrient losses. Thus, other potential alternatives could be a combination of surge irrigation, PAM application and a grass-lined tailwater ditch, use of straw-mulched furrows, or use of no-till with rill irrigation. However, additional off-site treatment may still be needed such as using constructed wetlands or detention ponds augmented with chemical coagulation treatment in order to meet strict reference conditions that would fully support aquatic life.

4. Conclusions

We used USEPA reference TN and TP maximum concentration values as indicators of full support of aquatic life to evaluate if soil conservation practices would improve water quality of return flows from rill irrigation. These soil conservation practices combined patch application of polyacrylamide (PAM) with an additional erosion control practice (check dams, surge irrigation, surface drains, and grass filter strips). Results showed that TN exceeded the USEPA reference value of 0.36 mg TN/L in all samples, while 96% of the samples exceeded the USEPA reference concentration value of 0.1 mg TP/L.

There was no treatment effect on reduction of NO_3–N or SP in irrigation runoff. Nevertheless, all samples showed NO_3–N concentrations below the USEPA drinking water standard of 10 mg/L. The only nutrient component in irrigation runoff that was strongly related to SL was PP concentration ($r = 0.87$). For TKN, significant concentration and load reduction between control and the other four erosion control practices ($P < 0.05$) occurred only in vineyard A. As for PP, the four PAM integrated control practices showed statistically significant effects with respect to the PAM control in vineyard B only. Although PAM is an excellent practice to control soil erosion, with widespread adoption in the Yakima River Basin, additional off-site treatment such as constructed wetlands or detention ponds augmented with chemical coagulation treatment may be needed for nutrient concentrations in irrigation return flows to meet reference conditions that would fully support aquatic life.

Acknowledgments

This research project was funded by the US Department of Agriculture – Cooperative State Research, Education, and Extension Service 406 Program and by the National Institute of Water Resources – US Geological Survey, Water Quality Program. Also the cooperation of Lower Yakima Valley irrigators and the Yakama Nation made this project possible. Mention of trade names or commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

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