Mitigating offsite movement of sediments from furrow-irrigated croplands in California's Central Valley

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Abstract

Irrigation tailwater can serve to transport sediment and particle-associated agricultural pollutants to nearby water courses. To help protect the biota of surface waters, we evaluated the use of polyacrylamide, PAM (a synthetic material that flocculates sediments when added to water), vegetated tailwater ditches, and sediment traps to mitigate losses of sediments from furrow-irrigated fields. In a two-year study, liquid PAM injected into irrigation water most effectively reduced the concentration of suspended sediments in runoff from different soil types. Dry tablet and granule PAM formulations were also effective, as long as they were placed in the furrows in a manner that promoted their dissolution in irrigation water moving down the furrows. Vegetated ditches resulted in intermediate reductions in suspended sediments in the tailwater, while the effectiveness of sediment traps was limited by insufficient holding time for the fine-grained particulates to settle out of the runoff.

Introduction

Erosion of soil from cropland and the transport of sediments into nearby surface water bodies via irrigation runoff can degrade the quality of surface waters through increased turbidity and sedimentation. Beyond the physical impacts of the sediment itself, the particles may carry potentially polluting substances such as nutrients and pesticides. For example, in the Central Valley of California, there are 11 water body segment listed as “impaired” under the draft 2008 Clean Water Act Section 303(d) list due to sediment toxicity of agricultural origin. There are many other segments impaired due to specific particle-associated pesticides, such as DDT, dieldrin, lindane, and pyrethroids. Pyrethroid insecticides, in particular, are widely used in California agriculture, and are commonly found in the sediments of creeks and agricultural drains at concentrations toxic to sensitive aquatic species (Weston *et al.*, 2004, 2008; Phillips et al., 2006). Pyrethroid insecticides are extremely water insoluble and bind tightly to finer particulate sediments. After being applied to fields, pyrethroids primarily move offsite attached to suspended sediments in irrigation and storm water runoff (Gan *et al.* 2005).

Some practices that have been used successfully to retain soil on croplands and mitigate the transport of sediments to surface water bodies include the use of polyacrylamide, PAM (a liquid or solid material synthesized from natural gas) added to water to stabilize the soil, (Sojka *et al.* 2007), vegetated ditches (Bennett *et al.* 2005; Lacas *et al.* 2005; NRCS 2008; Moore *et al.* 2008), and sediment traps or basins that retain tailwater long enough to allow particles to settle (NRCS 2003). The purpose of our study was to further evaluate PAM using a variety of application methods, and to contrast its effectiveness in concurrent trials with other potential mitigation techniques (vegetated ditches and sediment traps).

Materials and methods

Experimental sites and design

This project was conducted in 2006-07 in furrow-irrigated fields at the University of California at Davis and California State University at Chico. The Davis soil type was loam with 40.2% sand, 37.2% silt, and 22.6% clay and Chico soil was clay loam with 27.7% sand, 46.6% silt, and 25.7% clay. Both sites consisted of four to six plots with nine or ten, 5-foot beds (depending on the site and year) that were 600-feet long. Each plot was independent with respect to field management and irrigation runoff. In both years, Davis was planted with processing tomatoes and Chico with lima beans.

Gated aluminum pipe (Davis) or polypipe (Chico) was used to deliver groundwater to the test plots at an average flow rate of 12 to 20 gallons per minute (gpm) per furrow, with a turbidity reading of 3.5 NTU (U. S. EPA). Micrometer™ flow meters were used to measure the total applied irrigation water to each plot. Irrigation surface runoff from each plot flowed into a toe drain at the end of the furrows, then through either broadcrested weir flumes (Davis) or trapezoidal flumes (Chico) equipped with a stilling well and Global Water™ pressure transducer and datalogger to measure the runoff flow rate every minute.

The irrigation tailwater was then directed either into an earthen (unvegetated) ditch to represent an untreated control, or into vegetated ditches, or sediment traps, depending on the irrigation event and runoff treatment under evaluation. All runoff was then directed into a main drain with no outlet so as to avoid any contamination of surface waters. The following treatments were evaluated and replicated during each irrigation event or in subsequent irrigation events.

Polyacrylamide, PAM

Treatments consisted of control plots (no PAM application) and liquid PAM injected into the irrigation water using an aqueous formulation (PAM 25, 25% PAM, Terawet Inc.) or an oil-based formulation (Soilfloc 300E, 37% PAM, Hydrosorb Inc.), and dry PAM formulations (Hydrosorb) using both granules (88-90% PAM) and tablets (40% PAM). The liquid PAM was injected into the source water by a peristaltic pump to achieve PAM concentrations (active ingredient) of usually 1-7 mg/L, or up to 30 mg/L in one trial.

In early trials, placement of PAM tablets and granules in the furrows within a few feet of the gated pipe was attempted at both sites, but the PAM was quickly buried due to turbulence and resulting soil erosion caused by the incoming water, rendering it ineffective. Subsequently, the PAM granules (1 or 2 ounces, oz) or tablets (1 or 2) were placed in each furrow at either 100 feet or 300 feet or both distances from the gated pipe at the Davis site, and dissolved as the water flowed down the furrow. The concentration of the dry PAM formulations in the surface runoff was <0.2-0.5 ppm, but unknown in the water in the furrows, with some material left after each irrigation event. Different dry PAM placements were not investigated at the Chico site, but instead several methods of suspending PAM tablets in the source water were evaluated.

Water infiltration was determined as the difference between the cumulative amount of inflow and outflow during irrigation. Only the results of the 2007 PAM experiments are discussed herein because of liquid PAM injection problems in 2006.

Vegetated ditches

In 2006, three vegetated ditches, 160-feet long by 5-feet wide, and about 8-inches deep, were established at both Davis and Chico with tall fescue sod *(Festuca arundinacea).* This length was anticipated to be sufficient for handling the amount of tailwater expected for this research. In 2007, one vegetated ditch with similar dimensions was seeded with a mix of perennial ryegrass *(Lolium spp.)* and tall fescue at Chico the prior fall, at about 18 pounds, lb (8 kg, kilograms) per acre, ac. For both sites and years, the grasses formed a thick thatch, visually covering nearly 100% of the ground. The irrigation tailwater flowed through the flumes, then through the vegetated ditch at or below the height of the grasses.

Sediment traps

In 2007, three sediment traps were installed at each site that were approximately 60-feet long, 2-feet deep (at the water line) and 6.5-feet wide with sloped sides. The traps provided about 60 to 90 minutes of holding time, which was sufficient for particulates larger than coarse to fine silt to settle out. In addition, the traps were lined with plastic to prevent sidewall sloughing.

Data Collection

Each field site was irrigated once prior to evaluating the mitigation practices and the sediment in the runoff was found to contain no detectable pyrethroids (<1 ng/g). Subsequently, the fields were cultivated and a pyrethroid insecticide applied at each site at recommended field rates. Warrior® (lambda-cyhalothrin) was used at Davis at 0.03 lb ai/ac and Mustang® (zeta-cypermethrin) at Chico at 0.05 lb ai/ac. Within a few days of the applying the insecticides, the fields were irrigated and runoff collected under the different mitigation practices. Each irrigation event included the mitigation practice and a control plot with no mitigation. This process (field cultivation, pesticide application, and irrigation, unless otherwise noted) was repeated with five to six irrigation events per growing season.

Tailwater samples were collected from each plot approximately every 30-minutes from the onset of surface runoff until the water was turned off and flow had nearly ceased. Water samples were collected from the control and PAM plots just above the flumes that were used to measure surface runoff flow rate. For the vegetated ditches and sediment traps, tailwater samples were collected both before and after the runoff passed through the mitigation measure. Water samples (16.9 oz , 500 ml) were taken for total suspended sediment concentration, and analyzed by filtering a known volume of water on a Whatman 934-AH™ glass fiber filter, and weighing the dry particulate matter that was retained on the filter. The suspended sediment concentration data were combined with the flow measurements to estimate the average flow-weighted suspended sediment concentration when integrated over the entire irrigation event. Suspended sediment was also collected by continuous flow centrifugation of large volume (10-60 gallon or 37.8 to 227 liters) water samples, and the pyrethroid content analyzed by the methods of You et al. (2008).

Results

Suspended sediment concentrations in the control treatments (no mitigation practice) were highest for the first irrigation event at both Chico and Davis and declined with subsequent irrigation events during the season. Suspended sediment concentrations were also highest at the start of surface runoff for each irrigation event, and decreased over time. For example, suspended sediment concentrations at Davis typically were 0.5-2 g/L at the beginning of each irrigation event and declined to 0.1-0.3 g/L. At Chico, initial concentrations were 1-4 g/L and 0.3-0.7 g/L in the later stages of an irrigation event.

The duration of the irrigation events ranged from 228 to 314 minutes at Davis and 260 to 435 minutes at Chico. Maximum tailwater flow rates ranged from 80 to 90 gpm at Davis (43% average runoff) and from 30 to 72 gpm at Chico (18.9% average runoff). The rates of runoff were more variable at Chico depending upon whether and how deeply or lightly the soils were cultivated.

Polyacrylamide, PAM

Liquid PAM at concentrations of about 2.1 ppm (estimated from PAM injection and irrigation water flow rates) greatly reduced suspended sediment concentrations (Figure 1). In subsequent irrigation events, both liquid PAM (about 5 ppm) and PAM tablets placed 300 feet down the furrow substantially reduced suspended sediment concentrations (Figure 2). Higher initial sediment concentrations existed shortly after runoff started for the tablets, but after about 50 minutes of runoff, similar sediment concentrations occurred for both liquid and dry PAM treatments.

Similar suspended sediment concentrations occurred for both PAM tablets and granules for the August 14 irrigation event at Davis (Figure 3). The dry PAM material placed at both 100 and 300 feet down the furrow from the source water were slightly more effective compared to a single-location placement, however this behavior was not consistent for other irrigation events (Table 1).

In 20 combined PAM trials (15 at Davis, 5 at Chico) involving liquid and dry PAM (excluding placements at the head of the furrows and tablet suspension in the water), the percent reduction in the total sediment load due to the PAM treatments ranged from 57% to 92% (Table 1). In 60% of the trials, a reduction in suspended sediment concentration of greater than 80% was achieved, while a reduction of >90% was achieved in 25% of the trials.

PAM concentrations that ranged from 1.1 to 30 ppm in the source water achieved sediment reductions between 57% and 92% (Table 1). The smaller value resulted from terminating the PAM injection when the source water reached the end of the furrows, after which sediment concentrations increased to those of the control treatment. The average percent sediment reduction of liquid versus dry PAM treatments with values of 86.7% and 77.9%, respectively, were statistically indistinguishable (t-test, 0.05, p=0.108). The number of placements for dry PAM in the furrows was also statistically indistinguishable (p=0.217) with sediment reduction values of 73.6% and 83.0% for the single versus two placement treatments, respectively.

Suspending PAM tablets in the source irrigation water at the Chico site reduced the sediment load, but these treatments were not very effective compared to the liquid PAM treatments (Table 1). PAM treated soil from previous applications, and left undisturbed, reduced the sediment load in a subsequent irrigation by 45.4% at Davis and 47.8% at Chico (Table 1). No statistically significant differences were found in infiltrated amounts of water between control and PAM treated plots (Davis p=0.419 and Chico p=0.925). Average infiltrated amounts at the Davis site were 0.89 and 0.98-inches for the control and PAM treatments, respectively, and 1.85-inches for both treatments at the Chico site.

Vegetated ditches

Combining results from both Chico and Davis, the vegetated ditches significantly reduced total suspended sediments by 62% at 160 feet (p<0.1, n=9, ANOVA), compared with a gain in sediments in the earthen ditch due to erosion within the ditch, though non-significant (p>0.1, n=7, ANOVA) (Figure 4). The average total suspended sediment concentration at the beginning of the vegetated ditch was 0.34 g/L compared to 0.13 g/L at

160 feet. A typical irrigation used in this study of about 5-hour duration resulted in an average of 61 lb/ac (42 lb or 19 kg) of sediment reaching the head of the vegetated ditches. Thus, passage of water through the vegetated ditches prevented off-site movement of 62% of this total (26 lb or 12 kg) per irrigation event, with nearly 38 lb/ac of sediment retained.

Sediment traps

In 2007, the sediment traps significantly reduced suspended sediments by 39% in the first irrigation event ($p<0.05$, $n=3$, ANOVA) but not in the second and third combined (Figure 5). For the first irrigation event, the average sediment level above the traps was 0.98 g/L compared with 0.60 g/L below the traps. For the second irrigation event, the average sediment level above the traps was 0.21 compared with 0.19 g/L below the traps ($p>0.05$, $n=3$, ANOVA). With an average of 74 lb/ac (51 lb or 23 kg) of sediment (all sites and years combined) reaching the sediment traps during a typical 5-hour irrigation used for this study, the trap retained 29 lb/ac (20 lb or 9 kg) of this sediment (39%) in the first irrigation, and nearly none in the second irrigation.

Pyrethroid chemistry

Background concentrations of Warrior® and Mustang® in the suspended sediment in surface runoff at both Chico and Davis prior to applying these insecticides in our trials were below the minimum detection level of 1 ng/g in both years of our study. After applying the pesticides, for all treatments combined, the Warrior® treated plots at Davis had a median lambda-cyhalothrin concentration of 431.5 ng/g of dry sediment in the surface irrigation runoff, whereas runoff from the Mustang® treated plots contained cypermethrin at 162.5 ng/g.

There were no statistically significant differences in pyrethroid concentrations between the different treatments ($p>0.05$) (i.e., the treatments altered suspended sediment concentration, but not the pyrethroid concentration on that sediment). As a result, the level of particle-sorbed pyrethroid reduction achieved by the different treatments was equivalent to the amount of sediment reduced by the different treatments during an irrigation event. This relationship assumes the vast majority of pyrethroid is present on the suspended sediment rather than dissolved in the water, a reasonable assumption given the strong tendency of these insecticides to bind to soils and to be transported with the suspended sediments.

Discussion

Both liquid and dry PAM formulations were highly effective at reducing sediment loss in surface runoff with a reduction of more than 80% in suspended sediment loads with most uses. When using liquid PAM, the water-based PAM is recommended because the carriers in the oil-based PAM are toxic to some aquatic invertebrates at recommended field application rates (Weston *et al.* 2009). A PAM concentration of about 5-ppm in the irrigation source water is recommended when using liquid PAM. However, we also found concentrations as low as 1-ppm to effectively reduce sediments in irrigation tailwater, suggesting the need to try different rates on farms. For dry PAM, 1 to 2 ounces of PAM granules or 1 to 2 tablets per furrow appears suitable, as long as the material is placed at least 100 to 300 feet from the furrow head, where it will not become covered with eroded sediment as water enters a field.

The vegetated ditches in our trials were found to reduce the concentration of sediment in surface runoff by approximately 60%. This filtering process reduces the flow of suspended particles and associated pesticides, allowing them to settle out of the irrigation water where they are usually broken down to non-toxic forms by sunlight and microbial activity (Lacas *et al.* 2005). Vegetated ditches may also protect water quality via infiltration in the soil and the adsorption of pesticides on plant surfaces where they are also broken down by physical and biological processes (Moore *et al.* 2008).

Vegetated ditches should be wide and dense enough to maintain a shallow sheet-like flow depth at or below the height of the vegetation, to provide adequate contact between the flowing water and the vegetation. In our trials with surface runoff ranging from 30 to 90 gpm from the field, a 160-foot long by 5-foot wide grass-filled ditch with a water depth of about 5-inches, appeared to be sufficient to reduce sediments in irrigation tailwater by about 60%, though effectiveness is likely to be dependent on ditch length (Moore *et al.* 2008).

The sediment traps resulted in some reduction in sediments in surface runoff in the first irrigation, but not subsequent irrigation events. Sediment traps function by temporarily retaining the irrigation surface runoff, reducing the flow velocity and turbulence, enabling suspended sediments to settle out. Coarser grained or larger aggregated soil particles settle out of the runoff much more rapidly than finer grained silt and clay particles, on which the majority of the pyrethroids or other sediment-associated pesticides would be carried. As a result, the efficacy of the traps will depend on soil types and flow rates.

For higher flow rates and silty-loam soils, the retention time in the sediment traps will not be high enough to retain the water long enough to allow the fine silts to settle out before the water is released into drains. In these cases, larger tailwater ponds or return systems would be recommended. The sediment traps may have been more effective during the first irrigation event in our trials because the disruption in aggregate stability, particularly in the beginning of the season when fields are extensively cultivated for planting, resulted in higher levels of coarser particulates coming off fields, though we did not measure the particle size distribution in our traps.

The use of PAM, vegetated ditches, and sediment traps will help prevent sediments and sediment-associated pesticides such as pyrethroids from moving offsite when irrigation runoff occurs in furrow-irrigated fields. However, the degree of protection these mitigation practices will provide will depend on many factors including site-specific soil erosion characteristics and the volume and velocity of the irrigation tailwater. As a result, site-specific recommendations will be needed to determine how to best protect water quality from irrigation runoff on individual farms (Long *et al.* in press).

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Table 1. Percent suspended sediment reduction in irrigation tailwater with different PAM treatments, Davis and Chico, 2007. Distances in feet refer to how far the dry PAM was placed from the irrigation source water (gated pipe in our trials). Negative values indicate that the sediment concentration of the PAM treatment was greater than the control (no PAM) treatment.

PAM Treatment	**Sediment reduction (%)**	**Comments**
Davis – July 11		
Liquid	84.2, 91.8	Two plots: oil based, 7 ppm, 2.1 ppm
Tablets	-66.1	2 per furrow at 10 feet, covered by sediment
Granules	23.4	1 oz per furrow at 10 feet, mostly covered by sediment
Davis – July 24		
Tablets	86.7	2 per furrow at 300 feet
Davis – August 3		
Tablets	71.5	2 per furrow, 1 each at 100 feet and 300 feet
Liquid	81.5	Oil based, 5 ppm
Tablets	77.7	2 per furrow at 300 feet
Residual	45.4	Uncultivated furrows; liquid residual from July 24 irrigation
Davis – August 14		
Tablets	57.4	2 per furrow at 300 feet
Tablets	68.1	2 per furrow at 100 feet
Tablets	84.4	2 per furrow, 1 each at 100 feet and 300 feet
Granules	85.8	2 oz per furrow, 1 each at 100 feet and 300 feet
Liquid	78.0	Water based, 30 ppm
Davis – August 30		
Granules	90.5	2 oz per furrow, 1 each at 100 feet and 300 feet
Granules	79.3	1 oz per furrow at 100 feet
Davis – September 26		
Liquid	84.1, 91.9	Two plots: water based, 5 ppm each
Chico – June 5		
Tablet	-42.7	1 per furrow at furrow head, covered by sediment
Liquid	81.1	Oil based, 2.1 ppm
Chico – June 15		
Tablet	38.9	1 suspended in a porous bag in the furrow water
Liquid	57.0	Oil based, 5.9 ppm terminated after water reached end of furrows and thereafter sediment levels increased.
Chico – June 26		
Liquid	90.4	Oil based, 1.5 ppm
Chico – July 6		

Tablets	75.6	2 per furrow in 10-foot long uncultivated area at furrow head
Liquid	91.6	Oil based, 1.1 ppm
Chico – July 17		
Tablets	69.4	20 suspended in the water inside the source mainline
Residual	47.8	Uncultivated furrows; liquid residual from July 6 irrigation

Figure 1. Suspended sediment concentration (g/L) in irrigation tailwater during one irrigation event for control (no PAM) and liquid PAM treatments at about 2.1 ppm in the source water, Chico and Davis, 2007.

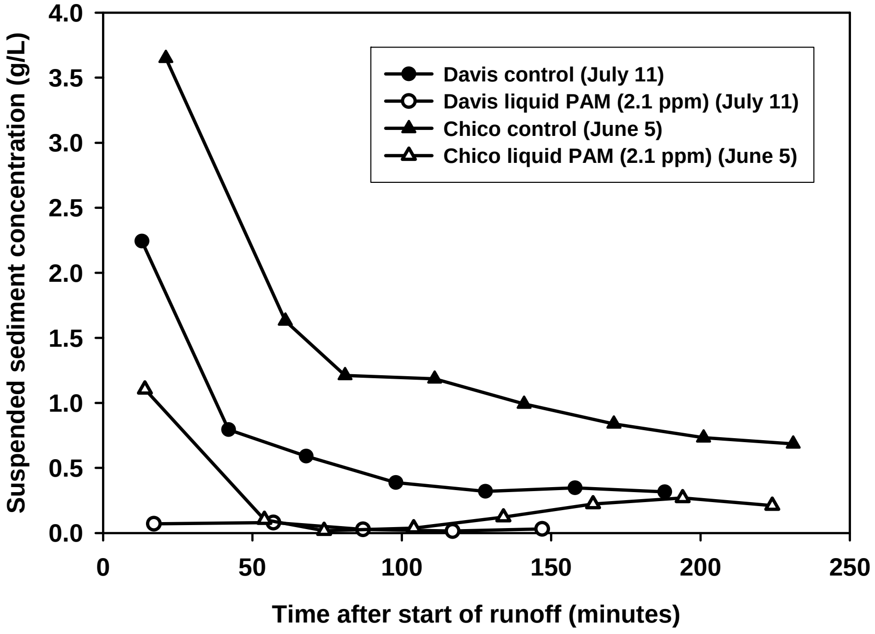

Figure 2. Suspended sediment concentration (g/L) in irrigation tailwater during one irrigation event for the control (no PAM), liquid PAM at about 5ppm in the source water, and two tablets per furrow placed at 300-feet from the source water, Davis, 2007.

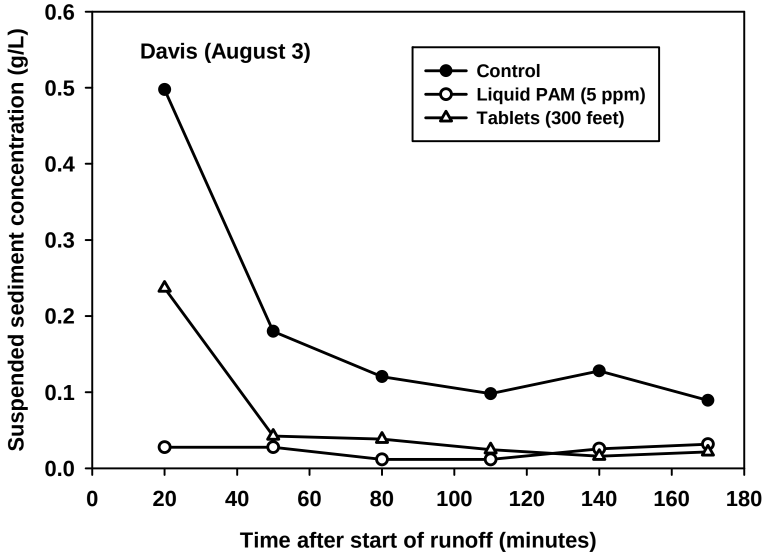

Figure 3. Suspended sediment concentration (g/L) in irrigation tailwater during one irrigation event for the control (no PAM) and two PAM tablets or two ounces of granules per furrow placed at100-feet, 300-feet, or both distances from the source water, Davis, 2007.

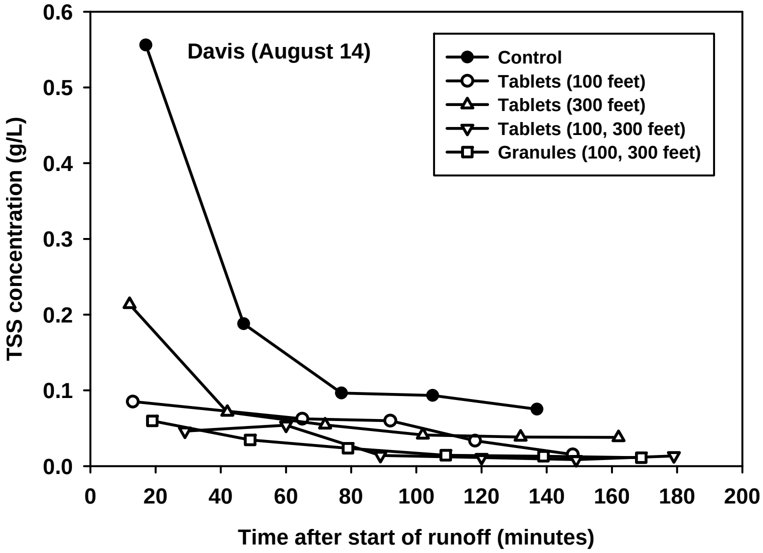

Figure 4. Effect of vegetated tailwater ditches on suspended sediment concentration (g/L) in irrigation tailwater compared with an earthen (unvegetated) ditch. Suspended sediments were reduced by 62% in the ditches at 160-feet, whereas the unvegetated ditches showed a gain in sediments due to soil erosion, though non-significant, NS.

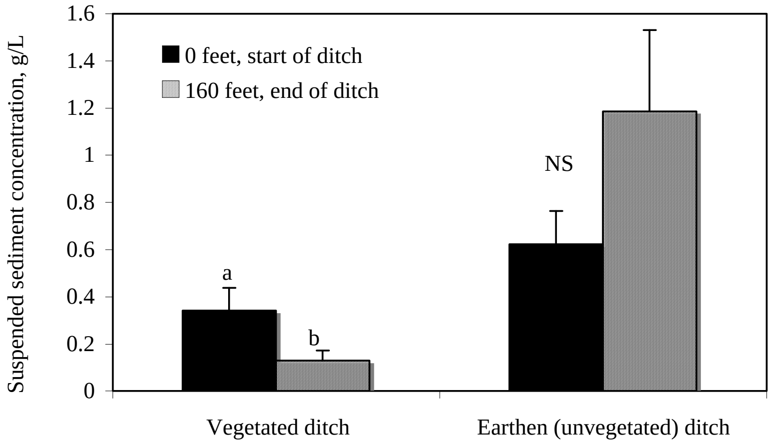

Figure 5. Effect of sediment traps on suspended sediment concentration (g/L) at the trap inlet and trap outlet in irrigation tailwater. Suspended sediments were significantly reduced by 39% in the first irrigation event, but not in subsequent (NS) irrigations.