Using polyacrylamide with sprinkler irrigation to improve infiltration

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ABSTRACT: Center-pivot irrigation systems often apply water at rates greater than the soil infiltration rate. Applying high molecular weight, water-soluble, anionic polyacrylamide (PAM) to the soil can improve infiltration and reduce soil erosion The objective of this study was to determine whether single and multiple PAM applications with sprinkler irrigation improved infiltration under field conditions. A two-year study conducted near Kimberly, Idaho, used a solid-set sprinkler system, and a one-year study conducted in Monte dos Alhos near Alvalade do Sado, Portugal, used a center pivot. At Kimberly, applying PAM with four irrigations (total applied PAM was 2.1 kg ha^{-1} in 2000 and 3.0 kg ha^{-1} in 2001) significantly reduced total measured runoff, from 5.9 mm (2000) and 9.2 mm (2001) for the control to 2.0 and 2.1 mm. Total measured soil erosion was also reduced from 52 and 34 kg ha^{-1} for the control to 21 and 5 kg ha^{-1} for the multiple PAM treatment. Applying similar or greater amounts of PAM with a single irrigation reduced erosion, but not runoff, compared with the control. In the Monte dos Alhos study, runoff was reduced by applying a total of 0.3 kg PAM ha^{-1} with a single irrigation (43 mm runoff) or three irrigations (65 mm runoff) compared with the control (111 mm runoff). Measured soil erosion was not significantly different among treatments. Applying PAM with multiple irrigations extended its effectiveness as long as the application rate was great enough to adequately stabilize the soil surface during the first irrigation.

Keywords: Center pivot, erosion, PAM, runoff, sprinkler irrigation

Although surface irrigation is used on most of the irrigated land in the world, use of sprinkler irrigation is increasing—primarily center-pivot systems. A new irrigation scheme under construction in southern Portugal, for example, will add 110,000 ha (272,000 ac) of center-pivot irrigated land by 2025 (HP, 1995). In the United States, about 45% of the irrigated land is sprinkler-irrigated, with 75% of that irrigated by center pivots (USDA, 1998).

Under ideal conditions, center-pivot irrigation systems should not cause runoff. However, soil and topographic variations, along with water supply and economic constraints, often compromise system designs. Application rates often exceed soil infiltration rates under the outer spans of center pivots. This is especially true when systems use low-pressure nozzles that have smaller wetted diameters.

Applying 10 mg L^{-1} (10 ppm), or about

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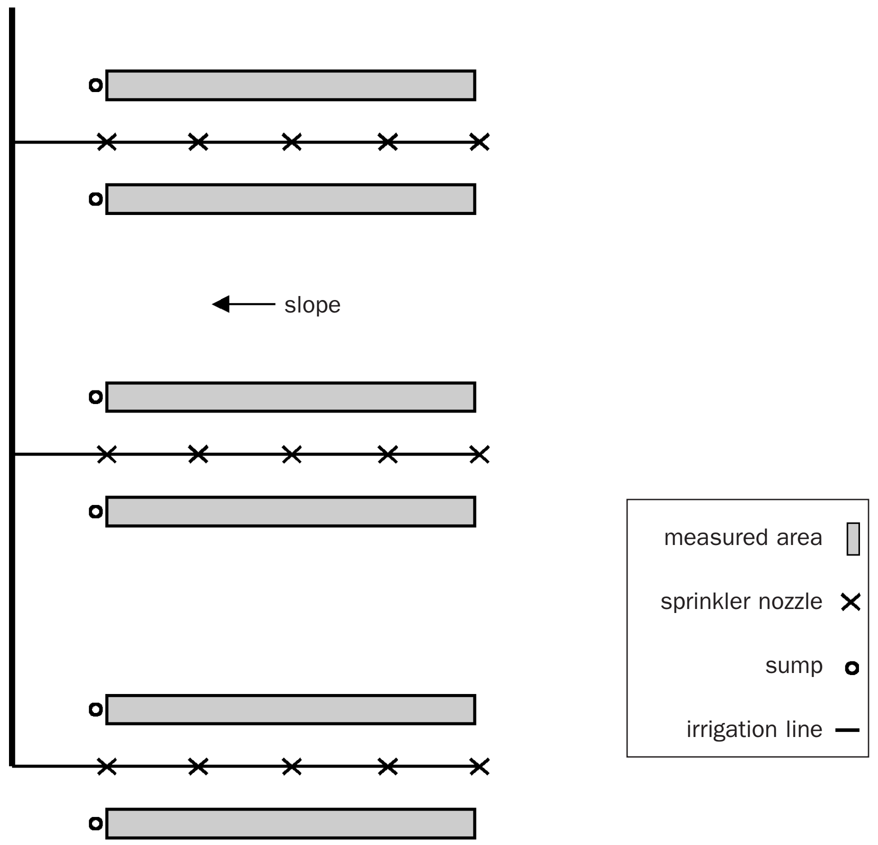
1 kg ha^{-1} (0.9 lb ac^{-1}), of anionic polyacrylamide (PAM) with surface irrigation water as it advances across a field can increase infiltration about 15% (Sojka et al., 1998) and reduce erosion more than 90% on research plots (Lentz et al., 1992; Sojka and Lentz, 1997). Santos and Serralheiro (2000) showed that PAM increased cumulative infiltration 15% to 20% on furrow-irrigated Mediterranean soils. Applying PAM to sprinkler irrigated land can also improve infiltration, which reduces runoff and soil erosion. Several laboratory studies have shown that spraying concentrated PAM solutions (500 mg L^{-1}[500 ppm]) on the soil surface at rates equal to or greater than 20 kg ha^{-1} (18 lb ac^{-1}) increased final infiltration rate and decreased soil erosion during simulated rainfall (Ben-Hur and Keren, 1997; Levy and Agassi, 1995; Levin et al., 1991; Smith et al., 1990). Under natural rain, spraying 5 or 20 kg PAM ha^{-1} (4.5 or 18 lb ac^{-1}) on the soil reduced annual runoff compared with the control (Stern et al., 1991). Other field studies have shown reduced erosion or runoff under moving sprinkler systems when 20 kg PAM ha^{-1} (18 lb ac^{-1}) was applied to the soil before irrigation (Levy et al., 1991; Stern et al., 1992). Lower PAM application rates can be effective when PAM is applied with irrigation water rather than sprayed directly on the soil surface. In laboratory studies with 1.9 m^2 soil boxes, applying 2 to 4 kg PAM ha^{-1} (1.8 to 3.6 lb ac^{-1}) at 10 to 20 mg L^{-1} (10 to 20 ppm) with sprinkler irrigation water reduced runoff by 70% and soil erosion by 75% compared with untreated soil, but these benefits decreased with subsequent irrigations without PAM (Aase et al., 1998). In a similar laboratory study, applying 1 kg PAM ha^{-1} (0.9 lb ac^{-1}) with three consecutive irrigations reduced cumulative runoff by 50% as compared with untreated soil, while applying 3 kg PAM ha^{-1} (2.7 lb ac^{-1}) with one irrigation only reduced runoff by 35% (Bjorneberg and Aase, 2000).

The objective of this study was to determine the effectiveness of applying PAM with sprinkler irrigation at economical rates under field conditions. This paper presents results of field studies conducted near Kimberly, Idaho, and in Monte dos Alhos near Alvalade do Sado, Portugal.

Figure 1
Runoff plot layout for Kimberly, Idaho, field studies in 2000 and 2001.



Methods and Materials

Kimberly, Idaho, field tests. Field plots near Kimberly, Idaho, were monitored during the 2000 and 2001 growing seasons. Plots were established on the same field both years, but in different areas within the field. The field was Portneuf silt loam (coarse-silty, mixed superactive, mesic Durinodic Xeric Haplocalcids) with a uniform 1.2% slope. Dry beans (*Phaseolus vulgaris* L.) were grown in 2000 with rows planted on ridges spaced 0.56 m (22 in) apart. Furrows were formed between alternate rows (1.12 m [44 in] spacing) so runoff would flow down slope. Spring wheat (*Triticum aestivum* L.) was grown in 2001. Furrows were formed 0.76 m (30 in) apart immediately after wheat was seeded. Wheat rows were 20 cm (7.5 in) apart in the same direction as the furrows.

The sprinkler irrigation system consisted of one irrigation line per plot with five nozzles (Wobblers®) spaced 4.6 m (15 ft) apart along each line. The irrigation lines were oriented in the same direction as the slope and crop rows. Each nozzle had a 103 kPa (15 psi) pressure regulator and an 8.73 mm (0.344 in) orifice diameter. The large orifice diameter, which was 20% larger than recom-

Table 1. PAM application rates (kg ha^{-1} active ingredient) for field studies near Kimberly, Idaho, and Monte dos Alhos, Portugal.

	Kimberly, 2000		Kimberly, 2001		Portugal, 2001	
Irrigation	Single	Multiple	Single	Multiple	Single	Multiple
1	4.1	0.7	3.1	0.8	0.3	0.1
2	0	0.4	0	1.0	0	0.1
3	0	0.3	0	0.6	0	0.1
4	0	0.7	0	0.6	-	-
Total	4.1	2.1	3.1	3.0	0.3	0.3

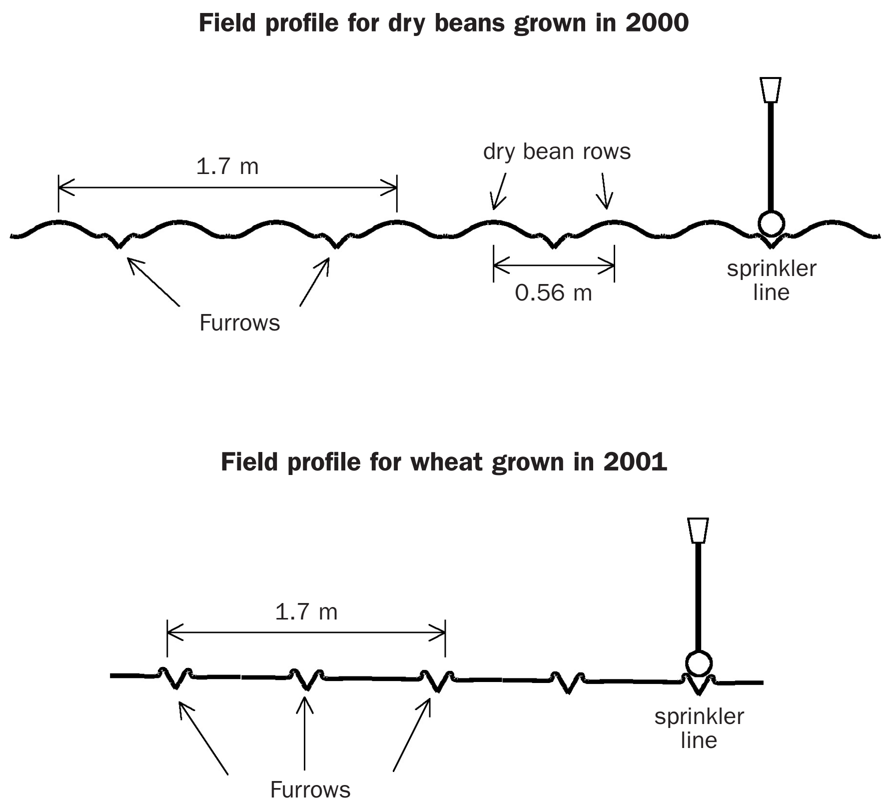
mended by the manufacturer, was used to give the desired application rate of 40 mm h^{-1} (1.5 in h^{-1}) and to cause runoff. Droplet kinetic energy was about 17 kJ m^{-3} (355 ft-lbf ft^{-3}), according to the Kincaid (1996) method of calculation. The Christiansen's uniformity coefficient (CU) was 79% for the 4.6 m (15 ft) wide area adjacent to the irrigation line. Irrigation lines were spaced 17 m (55 ft) apart so water was only applied on plots adjacent to the sprinkler line (Figure 1).

The three treatments for this study were control, single PAM application, and multiple PAM applications. Each treatment was irrigated separately, and the main irrigation pipes were drained after irrigation so no residual PAM would be applied to control plots. Irrigation time varied from 10 to 30 minutes, based on the time required before runoff occurred on the control plots. We wanted measurable, but not excessive, runoff from all treatments. Plots were typically irrigated every two or three days during the irrigation seasons. Rainfall was minimal during both irrigation seasons; 7 mm (0.28 in) in 2000 and 16 mm (0.63 in) in 2001. Because of the dry spring in 2000, the entire bean field was sprinkler irrigated twice in June before runoff plots were established. PAM treatments were applied after the dry beans were cultivated to control weeds in 2000.

PAM was applied by injecting a concentrated PAM solution into the main irrigation line. The concentrated solution was prepared by mixing a commercially available, high molecular weight, anionic, dry granular PAM (Superfloc® A836 from CYTEC Industries Inc., West Paterson, New Jersey) with tap water to produce a 1,000 mg L^{-1} (1,000 ppm) solution in 2000 and a 1,920 mg L^{-1} (1,920 ppm) solution in 2001. These solutions were more conveniently and easily metered into the irrigation flow than 30% or 50% active-ingredient liquid PAM products that are commercially available. For the single treatment, PAM was applied with the first irrigation at 4.1 kg PAM ha^{-1} (3.6 lb ac^{-1}) in 2000 and 3.1 kg PAM ha^{-1} (2.8 lb ac^{-1}) in 2001. For the multiple PAM treatment, PAM was applied at 3 to 3.5 mg L^{-1} (3 to 3.5 ppm) during the first four irrigations. Total applied PAM for the multiple treatments was 2.1 kg ha^{-1} (1.9 lb ac^{-1}) in 2000 and 3.0 kg ha^{-1} (2.7 lb ac^{-1}) in 2001 (Table 1). The field was not cultivated after PAM application either year.

Runoff was collected from an isolated area on both sides of the irrigation line (Figure 1).

Figure 2
Profile view of monitored area for 2000 and 2001 Kimberly, Idaho, field tests.



In 2000, the monitored area was 1.7 m by 18 m (5.6 ft by 60 ft), which was the area contributing runoff to the second and third furrows on each side of the irrigation line (Figure 2). Runoff in two furrows flowed into a covered sump, where the water and sediment were collected in a 15 L (4 gal) container. In 2001, the monitored area was 1.5 m by 24 m (5 ft by 80 ft), which collected runoff from the second, third, and fourth furrows on each side of the irrigation line (Figure 2). Runoff from the three furrows was again collected in a 15 L (4 gal) bucket in a covered sump. The monitored area was lengthened in 2001 by moving the sump 6 m (20 ft) down slope so the area around the sump was irrigated less, making runoff measurements easier.

Runoff was measured for all 15 irrigations in 2000 (excluding the two irrigations in June before runoff plots were established) and 16 of 18 irrigations in 2001. Soil loss was only occasionally measured during the irrigation season because of the time required to collect, filter and dry the sediment. To measure soil loss, water was decanted 24 hours after runoff collection to reduce the volume. The remaining water and sediment were filtered in the lab, dried and weighed. Soil loss was measured for six irrigations in 2000 and five irrigations in 2001. Shorter irrigation times were used for the control treatment after the seventh irrigation in 2001 because runoff became excessive while only minimal runoff occurred from the PAM treatments.

Soil water potential was monitored using Watermark® sensors installed at 10, 25, and 40 cm (4, 10, and 16 in) depths in one location in each plot. Sensors were read immediately before an irrigation and usually once or twice between irrigations. Two rain gauges were installed on one side of the irrigation line in each plot to monitor irrigation application rate.

A randomized block design was used with three treatments and four replications. Runoff was measured from two areas in each plot. A split-block analysis was used, but only the main effects of PAM treatments were considered. Treatment differences were calculated by least significant differences with $P<0.05$.

Table 2. Measured runoff from dry beans during 2000 growing season near Kimberly, Idaho.

Irrigation No.	Irrigation Date	Irrigation depth	Runoff Control	Runoff Multiple*	Runoff Single#	ANOVA probability
		mm	——— mm ———			
1	7/21/00	19	0.05 b†	0.03 b	0.09 a	0.01
2	7/24/00	13	0.04	0.01	0.02	0.08
3	7/26/00	9	0.08 a	0.00 b	0.01 b	0.05
4	7/29/00	21	1.52 a	0.36 b	0.79 ab	0.04
5	8/1/00	11	0.44 a	0.01 b	0.13 b	0.00
6	8/4/00	14	0.70 a	0.14 b	0.44 ab	0.03
7	8/7/00	13	0.33	0.08	0.06	0.09
8	8/9/00	14	0.33	0.13	0.18	0.14
9	8/11/00	13	0.53	0.27	0.42	0.08
10	8/14/00	13	0.24	0.10	0.14	0.48
11	8/16/01	10	0.32	0.19	0.15	0.06
12	8/18/00	10	0.53	0.27	0.46	0.22
13	8/21/00	10	0.37	0.21	0.30	0.52
14	8/24/00	10	0.30	0.11	0.22	0.24
15	9/1/00	10	0.18	0.13	0.28	0.20
Total		191	5.94 a	2.05 b	3.70 ab	0.03

* **Applied a total of 2.1 kg PAM ha^{-1} with irrigations 1-4.**

\# **Applied 4.1 kg PAM ha^{-1} with irrigation 1.**

† **Values in a row with the same letters are not significantly different based on LSD with P=0.05. Letters were not shown if ANOVA probability was >0.05.**

Monte dos Alhos, Portugal, field tests. Experimental plots were established in 2001 in Monte dos Alhos near Alvalade do Sado, Portugal, on a previously nonirrigated field. The field had a uniform slope of less than 1% and two soils, silty loam and sandy loam Fluvisols (FAO/UNESCO classification), in distinct areas. Surface-soil particle-size distributions show 20% clay, 35% silt, and 45% sand for the silty loam and 10% clay, 20% silt, and 70% sand for the sandy loam. The field was disked and roller-harrowed before planting corn (*Zea Mays* L.) at 76,000 seeds ha^{-1} (31,000 seeds ac^{-1}) in rows spaced 0.75 m (30 in) apart. The field was not cultivated after PAM application.

The sprinkler irrigation system consisted of a 300 m (980 ft) long center pivot with five spans that irrigated 31 ha (12.5 ac). Pressure in the main pipe was 425 kPa (60 psi), delivering water at 37 L s^{-1} (600 gpm). Droplet energy from the spray-type sprinklers was about 17 kJ m^{-3} (355 ft-lbf ft^{-3}), according to the Kincaid (1996) method of calculation. Christiansen's uniformity coefficient (CU) for the field was calculated as 94%. Peak application rate under the outer (fifth) span was 70 mm h^{-1} (2.8 in h^{-1}), with the outer span applying 10 mm (0.40 in) of water in 13 minutes.

The three treatments for each soil type were control, single PAM application, and multiple PAM applications (Table 1). PAM was applied by injecting a 30% active-ingredient, oil emulsion PAM (Superfloc® A-1883 RS from CYTEC Industries Inc., West Paterson, New Jersey) into the main irrigation pipe on the center pivot. This is a liquid formulation of the same type of PAM used in the Kimberly study. Application rates were on a product basis, not an active ingredient basis, so application rates were much less in Portugal. The single treatment was 1.0 kg ha^{-1} (0.9 lb ac^{-1}) of Superfloc applied with the first irrigation (0.30 kg PAM ha^{-1} [0.27 lb ac^{-1}]). The multiple treatment was 0.30 kg ha^{-1} (0.27 lb ac^{-1}) of Superfloc((0.10 kg PAM ha^{-1} [0.09 lb ac^{-1}]) applied with the first three irrigations, for a total of 0.30 kg PAM ha^{-1} (0.27 lb ac^{-1}) (Table 1). PAM injection was stopped after the pivot traveled beyond the PAM plots. A large buffer zone was irrigated between treated areas so no residual PAM would be applied to control plots. Irrigation times and depths varied during the growing season, following a typical irrigation scheduling practice used by farmers in the area. Plots were irrigated every two or three days, applying 10 to 23 mm (0.4 to 0.9 in) per irrigation. No rainfall occurred during the irrigation season, and no irrigation was applied before runoff plots were established.

Treatments were randomly assigned to pie-shaped areas on the two soil types within the field. Two runoff plots were located on each treatment on each soil for a total of 12 plots (3 treatments x 2 soils x 2 reps). Treatment differences were calculated by least significant differences with P<0.05. The silt loam plots were under the fifth span, while the sandy loam plots were under the third span, so application rate was less for the sandy loam than the silt loam. Runoff was collected from 2.56 m by 1.0 m (8.4 ft by 3.3 ft) rectangular frames with a V-shape on one of the shorter sides to collect runoff and deliver it through a plastic tube to a covered sump where water and sediment were collected. Runoff and soil loss were collected and measured for 20 of the 30 irrigations during the growing season.

Table 3. Measured soil loss from dry beans during 2000 growing season near Kimberly, Idaho.

Irrigation No.	Irrigation Date	Soil loss Control	Soil loss Multiple*	Soil loss Single#	ANOVA probability
		——— kg ha^{-1} ———			
1	7/21/00	11.9	11.9	10.6	0.73
2	7/24/00	1.8	0.6	1.5	0.29
3	7/26/00	6.7 a†	0.0 b	0.5 b	0.03
5	8/1/00	19.5 a	1.5 b	3.8 b	0.01
8	8/9/00	7.1	3.7	3.0	0.13
11	8/16/00	4.5	3.3	2.7	0.38
Total		51.6 a	20.9 b	22.2 b	0.00

* **Applied a total of 2.1 kg PAM ha^{-1} with irrigations 1-4.**

\# **Applied 4.1 kg PAM ha^{-1} with irrigation 1.**

† **Values in a row with similar letters are not significantly different based on LSD with P=0.05. Letters were not shown if ANOVA probability was >0.05.**

Results and Discussion

Kimberly, Idaho, field tests. Applying PAM with the first four irrigations significantly reduced runoff compared with the control for Irrigations 3 through 6 in 2000 (Table 2). The single PAM application also reduced runoff compared to the control for two irrigations. Less than 0.1 mm (0.004 in) of irrigation water ran off the plots during each of the first three irrigations, thus treatment differences were negligible for Irrigations 1 through 3. The multiple PAM treatment had 65% less total runoff than the control in 2000 (Table 2), which only increased cumulative infiltration 2%. Cumulative runoff for the irrigation season was 3.1%, 1.1%, and 1.9% of the applied irrigation water for the control, multiple and single treatments, respectively.

Both PAM treatments had significantly less soil loss than the control for Irrigations 3 and 5 in 2000 (Table 3). The high soil loss for Irrigation 1 can be attributed to extremely dry and loose furrow soil that was easily eroded with the initial runoff. Total soil loss for the six measured irrigations was also significantly less for the PAM treatments compared with the control (Table 3). PAM treatments reduced total measured soil loss 55% to 60% compared with the control.

In 2001, the single and multiple PAM treatments significantly reduced runoff compared with the control for Irrigations 2 through 7 (Table 4). More than 10% of the applied water ran off the control treatment during Irrigation 7. This excessive runoff greatly exceeded the capacity of the 15 L (4 gal) buckets used to collect runoff, requiring buckets to be switched several times during the irrigation. Thus, irrigation time for the control treatment was reduced after Irrigation 7 to decrease the amount of runoff. Irrigation time was not reduced for the PAM treatments so irrigation could meet crop water-use needs, according to Watermark® sensors. Although 20% to 60% more water was applied to the PAM-treated plots during Irrigations 8 through 17, runoff was not greater than the control (Table 4). Statistical differences among treatments were similar when runoff was compared as percent of applied water, but the probabilities were slightly less. (Data not shown.) Cumulative runoff for the 16 measured irrigations was significantly less for the multiple PAM treatment compared with the control (Table 4). The multiple PAM treatment had 77% less total runoff and 27% greater infiltration than the control. Cumulative runoff was 4.3%, 0.8%, and 1.5% of the applied irrigation water for the control, multiple, and single treatments, respectively.

Table 4. Measured runoff from spring wheat during 2001 growing season near Kimberly, Idaho.

Irrigation No.	Irrigation Date	Irrigation depth Control	Irrigation depth PAM	Runoff Control	Runoff Multiple*	Runoff Single#	ANOVA probability
		mm	mm	mm	mm	mm	
1	5/15/01	21	21	0	0	0	1.00
2	5/21/01	27	27	0.55 a†	0 b	0 b	0.00
3	5/24/01	18	18	0.70 a	0.11 b	0.07 b	0.03
4	5/29/01	24	24	0.28 a	0.04 b	0.03 b	0.05
5	6/1/01	17	17	0.77 a	0.01 b	0.01 b	0.00
6	6/5/01	16	16	0.76 a	0.01 b	0.01 b	0.00
7	6/7/01	16	16	1.97 a	0.05 b	0.08 b	0.00
8	6/9/01	8	19	0.66	0.20	0.67	0.27
10	6/14/01	9	14	0.07	0.18	0.24	0.17
11	6/16/01	9	20	0.06	0.11	0.23	0.28
12	6/18/01	10	19	0.05	0.36	0.74	0.16
13	6/20/01	12	14	0.61	0.15	0.48	0.27
14	6/22/01	12	14	0.85	0.28	0.44	0.35
15	6/25/01	11	13	0.60	0.14	0.27	0.15
16	6/27/01	13	17	0.77	0.23	0.32	0.21
17	6/29/01	13	17	0.51	0.25	0.38	0.70
Total		215	264	9.21 a	2.13 b	3.98 ab	0.05

* Applied a total of 3 kg PAM ha^{-1} with irrigations 1-4.

\# Applied 3.1 kg PAM ha^{-1} with irrigation 1.

† Values in a row with the same letters are not significantly different based on LSD with P=0.05. Letters were not shown if ANOVA probability was >0.05.

Both PAM treatments significantly reduced soil loss for three of the five irrigations measured in 2001 (Table 5). Note that soil loss was not different among treatments during irrigation 12 when 19 mm (0.75 in) was applied on the PAM plots compared with 10 mm (0.40 mm) on the control. Total soil loss for these five irrigations was reduced 80% to 85% by applying PAM.

The single application of PAM was more effective the second year than the first (Tables 3 and 5) although more PAM was applied the first year (Table 1). The single treatment consistently had less runoff than the control in 2001 while differences were inconsistent in 2000. The multiple treatment consistently had less runoff than the control in both years (Tables 3 and 5). The effectiveness of PAM applied with a single irrigation can be reduced with each successive irrigation as PAM-treated soil erodes. Applying PAM with multiple irrigations can improve the effectiveness by

Table 5. Measured soil loss from spring wheat during 2001 growing season near Kimberly, Idaho.

Irrigation No.	Irrigation Date	Soil loss Control	Soil loss Multiple*	Soil loss Single#	ANOVA probability
		$kg\ ha^{-1}$	$kg\ ha^{-1}$	$kg\ ha^{-1}$	
3	5/24/01	7.5 a†	1.4 b	2.5 b	0.02
4	5/29/01	5.7 a	0.8 b	1.2 b	0.02
5	6/1/01	11.0	1.1	0.2	0.11
6	6/5/01	8.9 a	0.6 b	0.4 b	0.00
12	6/18/01	0.5	1.0	2.4	0.10
total		33.5 a	5.0 b	6.7 b	0.00

* Applied a total of 3 kg PAM ha^{-1} with irrigations 1-4.

\# Applied 3.1 kg PAM ha^{-1} with irrigation 1.

† Values in a row with the same letters are not significantly different based on LSD with P=0.05. Letters were not shown if ANOVA probability was >0.05.

Table 6. Measured runoff from silty loam plots during 2001 growing season in Monte dos Alhos, Portugal.

Irrigation No.	Irrigation Date	Irrigation depth	Runoff Control	Runoff Single#	Runoff Multiple*	ANOVA probability
		mm	mm			
1	6/21/01	10	0.02	0.00	0.00	0.46
2	6/22/01	10	1.17	0.15	0.15	0.55
3	6/27/01	17	7.88 a	1.78 b	0.06 b	<0.01
8	7/10/01	23	13.57	3.76	10.25	0.16
10	7/17/01	23	13.68	7.42	13.26	0.19
12	7/24/01	23	13.77 a	3.24 b	13.43 a	0.02
14	7/31/01	23	13.74 a	9.61 b	13.87 a	0.03
15	8/2/01	23	12.45 a	5.57 b	2.22 b	<0.01
16	8/7/01	10	1.20	0.27	0.27	0.14
17	8/9/01	23	7.77	4.90	1.44	0.28
20	8/17/01	14	2.44	0.83	0.74	0.33
21	8/18/01	14	5.57 a	0.98 b	1.56 b	0.05
22	8/19/01	14	6.72 a	1.25 b	0.39 b	0.04
24	8/24/01	11.5	3.82	0.98	3.05	0.60
25	8/27/01	10	0.88	0.19	0.98	0.63
26	8/29/01	10	0.68	0.29	1.17	0.70
27	8/30/01	10	0.82	0.23	0.78	0.78
28	9/4/01	10	1.56	0.34	0.51	0.67
29	9/7/01	10	1.11	0.37	0.49	0.76
30	9/13/01	14	1.71	1.02	0.45	0.71
Total		291.0	110.58 a	43.18 c	65.06 b	<0.01

Applied a total of 0.3 kg PAM ha^{-1} with irrigation 1.

* Applied 0.3 kg PAM ha^{-1} with irrigations 1-3.

† Values in a row with the same letters are not significantly different based on LSD with P=0.05. Letters were not shown if ANOVA probability was >0.05.

repeatedly treating the soil. Because dry beans are a row crop, more of the soil was exposed to water-drop impact and erosion than with small grain. Furthermore, about 5% of the applied water ran off the single treatment during the first irrigation when PAM was applied in 2000, but no runoff occurred during the first irrigation in 2001, so all the applied PAM remained on the soil.

Although applying PAM improved infiltration, the additional infiltration did not improve crop yield either year. Average dry bean yield was 2.6 Mg ha^{-1} (2300 lb ac^{-1}) in 2000, and average wheat yield was 11 Mg ha^{-1} (170 bu ac^{-1}) in 2001. More than 95% of the applied water infiltrated for all treatments in 2000 and 2001. Applying PAM in 2000 only improved total infiltration by 1% to 2%, which was not enough additional water to cause a measurable increase in dry bean yield. About 20% more water infiltrated on the PAM treatments (262 mm [10.3 in] for multiple and 260 mm [10.2 in] for single) compared with the control (206 mm [8.1 in]) in 2001, but the control evidently had sufficient soil water, so crop yield was not reduced. The exceptional wheat yield may have resulted from a "border effect" from the small well-water plot areas surrounded by poorly watered borders. Furthermore, runoff flowed away from the plots, so water did not accumulate in an area where it could reduce crop yield, which could occur in low areas on a production field.

Monte dos Alhos, Portugal, field tests. The infiltration rate on the sandy loam plots exceeded the irrigation application rate, so no runoff occurred. Runoff occurred on the silty loam plots where the application rate was greater (greater distance from the pivot point) and the infiltration rate was less. Applying PAM significantly reduced runoff from silty loam plots during the 2001 growing season compared with the control (Table 6). The single PAM application had 67% less total runoff than the control treatment; the multiple PAM treatment had 41% less runoff than the control. Comparing PAM treatments, the single application had 34% less runoff than the multiple treatment. Cumulative runoff for the irrigation season was 38%, 15%, and 22% of the applied irrigation water for the control, single, and multiple treatments, respectively. Single PAM application also had 44% less runoff than the multiple applications under the particularly intense Irrigations 8 through 15 when 23 mm (0.91 in) depths were applied to the field, significantly reducing runoff for two of the five measured irrigations (Table 6). During those intense irrigations, 58%, 26%, and 46% of the applied water ran off from the control, single, and multiple treatments, respectively. The high runoff in the multiple PAM application plots might be attributed to the partitioning and application of PAM in three small applications of 0.1 kg ha^{-1} (0.09 lb ac^{-1}), resulting in a deficient coating of the soil surface. Santos et al. (2001) had concluded from laboratory tests with PAM application that the relatively low clay content, which acts as a cementing agent to stabilize soil aggregates, and the relatively high silt content, which weakens soil structure, might explain the low intake rate and low soil loss observed in the silty loam plots. With less silt and higher sand content at the soil surface, no runoff was observed on sandy loam control and PAM plots any time during the growing season. In contrast, surface crusting and sealing were observed to quickly form on the silty loam control and multiple PAM plots, inducing high runoff from the beginning of the irrigation season.

No soil loss occurred on the sandy loam plots because all of the irrigation water infiltrated. PAM treatments had little or no effect on measured soil loss from the silty loam plots. Soil loss was only significantly different among treatments for two of the 20 irrigations (Table 7).

Applying PAM with sprinkler irrigation controlled runoff at both locations. However, the best application strategy was different for each location. In Idaho, applying PAM with multiple irrigations increased infiltration more than applying PAM with a single irrigation. The opposite was true in Portugal, where the single application increased infiltration more than the multiple applications. One reason for the apparent conflicting results may be the low application rates that were used in Portugal. About the same amount of active ingredient of PAM was applied with the single application in Portugal as with any of the four irrigations of the multiple treatment in Idaho (Table 1). The PAM application rate used for the multiple treatment in Portugal was probably

Table 7. Measured soil loss from silty loam plots during 2001 growing season in Monte dos Alhos, Portugal.

Irrigation No.	Irrigation Date	Irrigation depth	Soil loss Control	Soil loss Single#	Soil loss Multiple*	ANOVA probability
		mm	kg ha^{-1}			
1	6/21/01	10	4.43	0.00	0.00	0.47
2	6/22/01	10	2.58	4.43	16.24	0.62
3	6/27/01	17	1.34	0.59	3.69	0.62
8	7/10/01	23	5.89	6.94	3.54	0.11
10	7/17/01	23	6.04 a	2.68 b	2.69 b	0.01
12	7/24/01	23	3.00	2.46	3.72	0.58
14	7/31/01	23	4.96	1.91	3.66	0.21
15	8/2/01	23	1.83	2.80	3.56	0.64
16	8/7/01	10	10.54	1.74	4.43	0.22
17	8/9/01	23	3.48	3.04	6.86	0.09
20	8/17/01	14	20.69	19.38	39.14	0.58
21	8/18/01	14	3.87	6.09	8.86	0.08
22	8/19/01	14	3.91	5.93	8.86	0.88
24	8/24/01	11.5	6.88	4.50	1.56	0.86
25	8/27/01	10	4.87	1.11	1.55	0.48
26	8/29/01	10	6.50	1.48	1.48	0.39
27	8/30/01	10	13.66	0.92	2.22	0.19
28	9/4/01	10	2.35	4.05	4.26	0.92
29	9/7/01	10	2.91b	19.67 a	3.10 b	0.04
30	9/13/01	14	3.16	6.00	3.37	0.73
Total		291.0	112.91	95.71	122.77	0.80

Applied a total of 0.3 kg PAM ha^{-1} with irrigation 1.

* Applied 0.3 kg PAM ha^{-1} with irrigations 1-3.

† Values in a row with the same letters are not significantly different based on LSD with P=0.05. Letters were not shown if ANOVA probability was >0.05.

too low to stabilize the soil surface and enhance infiltration. PAM application rates should be based on active ingredient, not "as supplied" to be sure enough PAM is applied to be effective.

Summary and Conclusion

Applying PAM with sprinkler irrigation was shown to increase infiltration in both the United States and Portugal. Applying PAM with multiple irrigations was as good or better than applying the same amount of PAM with a single irrigation, provided that the PAM application rate with any irrigation was sufficient to stabilize the soil surface. Applying PAM with multiple irrigations reduces the chance of skips or poor coverage caused by application problems during a single irrigation. Furthermore, PAM-treated soil can gradually erode with subsequent irrigations, reducing the effectiveness of a single application faster than multiple applications.

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