Changes in Soil Test Phosphorus and Phosphorus in Runoff From Calcareous Soils Receiving Manure, Compost, and Fertilizer Application With and Without Alum

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Abstract: Intensification of the dairy industry in southern Idaho has led to the overapplication of manures and a buildup of soil phosphorus (P), which is a potential threat to water quality in the region. As the use of alum has been shown to reduce both soluble manure P and runoff P from alum-treated manures, the objective of this study was to determine if surface applications of alum to dairy manure and compost before soil incorporation would reduce P losses under furrow irrigation on a calcareous soil. The effects of manure, compost, and fertilizer application with and without alum treatment on soil P, runoff P, and aluminum under furrow irrigation, crop yield, tissue P concentrations, and P removal during a 4-year period were investigated in Kimberly, Idaho, on a Portneuf silt loam (coarse-silty, mixed superactive, mesic Durinodic Xeric Haplocalcids). Fertilizer and manure addition had the greatest potential to increase soluble P in soils compared with compost, which translated to greater soluble P losses with irrigation in some instances. The addition of alum to manure did not have any effect on soil-extractable P or soluble P losses from furrow irrigation and therefore, when surface applied to manure before incorporation, is not a good best management practice for stabilizing P in manure-treated calcareous soils.

Key words: Phosphorus, manure, calcareous soil, irrigation

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The state of Idaho has recently experienced rapid growth of the dairy industry. The number of milk cows in Idaho has increased approximately 80% in the past decade, with a 110% increase in milk production (USDA NASS, 2007). Idaho is the second largest milk producer in the 12 western US states and has become the third largest milk-producing state in the United States. In 2006, there were 477,193 milking cows in Idaho, with 71% of these being located in the Magic Valley region of southern Idaho (UDI, 2007).

The concentration of dairy production in the Magic Valley has led to increased land application of manure from these operations and, in some cases, overapplication of manure nutrients. Of particular concern is phosphorus (P) loading both on production sites and at field manure application sites. Traditionally, manure has been applied to meet the nitrogen (N) requirement of crops, which overapplies P, because of the low N/P ratio of most manures (Mikkelsen, 2000). This practice builds up soil test P concentrations in regions dominated by concentrated animal production sites (Kellog and Lander, 1999).

In response to the buildup of soil P and the potential impact on water quality, the US Department of Agriculture Natural Resource Conservation Service requires that manure application to high P soils be based on either crop P requirements, a threshold soil test P concentration, or the use of a Phosphorus Site Index (NRCS, 2003). In areas with overly high soil test P concentrations, manure applications are either prohibited or limited to a crop P removal rate, which puts pressure on producers having a limited land base yet substantial production of manure at their facilities.

As many producers in southern Idaho have exceeded the threshold soil test P concentration, there is a need to stabilize P applied in manures to decrease the potential risk of P transfer from manure-amended soils to surface waters in the region. One potential tool for stabilizing P in manures and manure-amended soils is the use of chemical treatments such as alum (Moore and Miller, 1994). Dou et al. (2003) reported that soluble manure P decreased by 99% when alum was applied to dairy manure at an aluminum (Al)-to-P molar ratio of 1.33. Meals et al. (2008) reported that manure soluble P concentrations were reduced up to 79% when alum-based water treatment residuals were mixed with liquid dairy manure. Several studies have evaluated the impacts of land-applying alum-treated poultry litter on runoff P losses and found decreases of 50% to 84% in soluble reactive P when litter was treated with alum versus untreated litter (Smith et al., 2004; DeLaune et al., 2006; Sistani et al., 2006). Smith et al. (2001) reported an 84% decrease in soluble reactive P in runoff from plots receiving alum-treated swine manure versus untreated manure.

As the use of alum has been shown to reduce both soluble manure P and runoff P from alum-treated manures, the objective of this study was to determine if surface applications of alum to dairy manure and compost before soil incorporation would reduce P losses under furrow irrigation on a calcareous soil.

MATERIALS AND METHODS

Experimental Design and Treatments

An experiment was initiated in 2003 on a Portneuf soil (coarse-silty, mixed superactive, mesic Durinodic Xeric Haplocalcids) under furrow irrigation at the Northwest Irrigation and Soils Research Laboratory in Kimberly, Idaho. Initial soil properties in the 0- to 15-cm depth are shown in Table 1. The soil had a low soil test P concentration (3.76 mg kg^{-1} Olsen P), low organic matter content (0.79%), and a lime content of approximately 5%. The experimental design was a standard split plot design with whole-plot factor in a randomized complete block design with four replications. The whole-plot factors consisted of four treatments: fertilizer, manure, compost, and a control with the subplot treatment being alum versus no alum application. Whole plots were 15 m wide × 31 m long. Plots were split parallel to the irrigation furrows to make 7.5-m × 31-m subplots.

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TABLE 1. Initial Soil Properties (Fall 2003) Before Manure Application

Soil Property	Mean	SE
Sand-silt-clay, %	22-56-22	N/A
Organic C, %	0.79	0.02
Lime, %	4.56	0.57
NO_3-N, mg kg^{-1}	14.1	1.1
NH_4-N, mg kg^{-1}	6.37	0.34
Olsen P, mg kg^{-1}	3.7	0.4
WSP, mg kg^{-1}	4.0	0.4
Total P, mg kg^{-1}	622.9	6.4
Total Al, mg kg^{-1}	21,015	270
Total Ca, mg kg^{-1}	17,403	2003
Total Fe, mg kg^{-1}	20,306	229
Total Mn, mg kg^{-1}	875	15

Means and SE are of the whole plots.

Potatoes (*Solanum tuberosum*) were grown in 2004, barley (*Hordeum vulgare*) in 2005, and dry bean (*Phaseolus vulgaris*) in 2006. Potatoes were planted in hilled rows with 0.91-m row spacing. The potato crop was plowed under and no yield or plant samples collected because of a Colorado potato beetle infestation. Barley was seeded with a grain drill in 0.2-m row spacing. A plot combine harvested 2-m × 30-m area in the center of each plot to determine barley yield. Dry bean was planted with 0.6-m row spacing with a conventional planter. Two rows, 15 m long, were harvested with a plot combine to determine dry bean yield.

Application of treatments was based on target P application rates of 75, 109, and 162 kg P ha^{-1} for 2003, 2004, and 2005, respectively, with control plots receiving no P application. All materials were applied in the fall, after harvest, which is typical of manure application in this region. A blanket application of urea was applied at rates of 240 and 100 kg ha^{-1} in the spring of 2004 and 2005 to ensure that N was not a limiting factor for plant production; in 2006, there was no N application as soils were sufficient in N for dry bean production. The application rates for total P (TP), water-soluble P (WSP), N, and carbon (C) are shown in Table 2. After treatment application in 2003 and 2004, alum was surface applied to the subplots at a rate that would provide a 1:1 molar ratio of manure TP to Al, which is the recommended application rate. The alum application rate in 2005 was at a P/Al molar ratio of 1:0.5 because of limited alum available for application. After alum application, all plots were disked to incorporate treatments into the top 10 cm of soil.

Manure Collection and Characterization

The P fertilizer used in this study was monoammonium phosphate (MAP, 11-52-0). The manure and compost used were manure from an open lot dairy located near the experimental station and compost obtained from a commercial nursery. Manure is typically scraped from the lot surfaces and stockpiled in the lots until land application. The compost consisted of manure from a free-stall dairy operation, which was composted (via windrow) locally. As manures on open lot dairies are scraped and stockpiled in the center of the lots once daily, application of manure treatments and mixing of treatments into manures is not practical. Once manure is removed from the lots, it is generally either field applied or placed into windrows for composting. Once in windrows, application of manure treatments is not easily accomplished. As it is not practical to apply chemical treatments to manure and compost before land application in the present manure management systems, alum was applied after the materials were applied to the plots. This allowed for maximum interaction of alum and the manure or compost, after which all of the treatments were incorporated into the soils. It was hoped that this would simulate application of alum treatment in poultry houses, where surface applications are made to the litter (Choi and Moore, 2008).

Properties of manure and compost applied over the study are shown in Table 3. Manures and composts were analyzed for the following: (i) total elements (Ca, Fe, Mn, P) by microwave-assisted digestion of a 0.5-g dried sample with 8 mL of concentrated HNO_3 and 2 mL of 30% H_2O_2 and quantified by inductively coupled plasma optical emission spectroscopy (ICP-OES) detection; (ii) WSP by 1:100 wt/vol using deionized water, shaken for 1 h, and filtered with a 0.45-μm Whatman filter with P analysis by ICP-OES; and (iii) total N and C determined by combustion of a 50-mg sample in a FlashEA1112 (CE Elantech, Lakewood, NJ). Dried plant samples were digested by microwave-assisted digestion with 2 mL concentrated HNO_3 and 2 mL 30% H_2O_2 and analyzed for P, Ca, Fe, K, Mg, and Mn by ICP-OES. Total P output from plots was calculated by multiplying the total yield per plot by tissue P concentration.

Soil Collection and Characterization

Initial soil samples (0–15 cm) were collected from each main plot (n = 16) in the fall of 2003 before treatment application.

TABLE 2. Application Rates of TP, WSP, Total N, and Total C From 2003 to 2005 on Manure- and Compost-Treated Plots

	Application Rate	TP	WSP	N	C
	Mg ha^{-1}	----------kg ha^{-1}----------			
Manure 03	24.4	75	61	556	8421
Compost 03	32.9	63	10	501	5957
Fertilizer 03	0.3	59	59	29	
Manure 04	32.6	109	70	736	11,109
Compost 04	63.4	109	11	550	6551
Fertilizer 04	0.20	47	47	23	
Manure 05	33.0	162	79	732	8776
Compost 05	42.3	162	6	436	5259
Fertilizer 05	0.7	159	159	78	

TABLE 3. Chemical Properties of the Manures and Composts Applied to Plots in 2003–2005

	WSP	N	C	P	Ca	Fe	Mn
	----------------- mg g^{-1} -----------------						
Manure 03	2.5	22.6	342.2	3.0	15.6	1.9	0.1
Compost 03	0.3	15.1	179.7	1.9	11.7	4.3	0.1
Manure 04	2.1	22.4	337.9	3.3	13.4	1.9	0.1
Compost 04	0.2	8.6	102.4	1.7	11.2	4.5	0.1
Manure 05	2.4	22.0	263.8	4.9	18.5	3.4	0.2
Compost 05	0.2	10.2	123.1	3.8	17.9	9.8	0.3

C: total carbon; Ca: total calcium; Fe: total iron; Mn: total manganese; N: total nitrogen, WSP: water soluble phosphorus.

Soil samples (0–15 cm) were then collected from all plots ($n = 32$) each year from 2004 to 2007 before planting in the spring. To determine potential P leaching over time, 15- to 30-cm samples were collected in 2005–2007, and 30- to 46-cm samples were collected in 2006 and 2007. All samples were air dried in a forced-air oven, ground to pass through a 2-mm screen, and analyzed for bicarbonate-extractable P (Olsen P; Olsen et al., 1954), WSP (1:100 soil-deionized water, shaken for 1 h, filtered with a 0.45-μm Whatman filter), and TP (microwave-assisted digestion of a 0.25-g dried sample with 9 mL of concentrated HNO_3 and 3 mL of concentrated HCl). Both TP and WSP were quantified by ICP-OES, whereas Olsen P was quantified using the colorimetric method of Murphy and Riley (1962). In addition, the initial soil samples collected in 2003 before manure application were analyzed for the following: soil nitrate (NO_3^-) and ammonium (NH_4^+) determined by shaking 12.5 g of soil with 50 mL of 2 *M* KCl for 30 min followed by filtration with Whatman no. 42 filter paper with N determined colorimetrically by flow injection analysis, soil organic C using the method of Walkley and Black (1934), calcium carbonate equivalent (percentage lime) determined with the titrimetric method of Allison and Moodie (1965), and particle size determined by the hydrometer method (Gee and Bauder, 1986).

The relative P extractability for WSP and Olsen P was calculated in the 0- to 15-cm surface soil samples of each treated plot in 2004–2006. This calculation gives an indication of the increase in soil test P above the control per unit of P applied and therefore illustrates the ability of each treatment to increase soil test P. The relative P extractability for WSP and Olsen P in soils amended with manure, compost, or fertilizer P was calculated as follows:

$$\text{Relative P Extractability} = (\text{Soil P}_{\text{amended}} - \text{Soil P}_{\text{Control}}) \div \text{P}_{\text{applied}}$$

where Soil P_{amended} is the WSP (or Olsen P) for soil treated with manure, compost, or fertilizer; soil P_{control} is the WSP (or Olsen P) for soil in control plots; and P_{applied} is the amount of P applied with each treatment.

Irrigation and Runoff Water Characterization

Plots were furrow irrigated by gated pipes with spigot valves. The irrigation water source was the Snake River with typical chemical analysis of pH = 8.2, electrical conductivity = 0.5 dS m^{-1}, and sodium adsorption ratio = 0.7. There was an irrigation furrow between each potato row (0.91-m spacing), and alternate furrows were irrigated during each irrigation. Furrow spacing was 0.76 m for barley, and every furrow was irrigated during each irrigation. Furrow spacing was 1.1 m for dry beans, with two dry bean rows between irrigated furrows.

Irrigation runoff was monitored during the first three irrigations in 2004 (potato) and the first two irrigations during both 2005 (barley) and 2006 (dry bean). Inflow and runoff were measured for one furrow in each subplot. Furrow inflow rate was measured by the time required to fill a known volume (3.8 L). Inflow rate, which ranged from 12 to 24 L min^{-1}, was periodically checked during each irrigation to ensure that inflow rate was the same for each monitored furrow.

Furrow runoff was monitored at the end of each plot (31 m from the gated pipe). Small trapezoidal flumes were installed in furrows for measuring flow rate and allowing water sample collection. Sediment concentration was measured by the volume of sediment settled in 1 L Imhoff cones after 30 min, which is highly correlated with sediment mass (Sojka et al., 1992). Furrow flow rate was measured, and samples (sediment and water) were collected 15 min after water advanced past the flume. The following three measurements were made at 30-, 30-, and 60-min intervals, and two to three additional measurements were made at approximately 2-h intervals during the remaining irrigation time. A 60-mL sample of water was filtered (0.45 μm) within 5 min of collection and stabilized with saturated boric acid to stabilize P concentrations during storage. An unfiltered 60-mL water sample was collected and stored for total P determination. Filtered samples were analyzed for soluble P and Al using ICP-OES, whereas unfiltered samples were digested (persulfate digestion; American Public Health Association, 1992) and analyzed for TP by ICP-OES. Furrow runoff volume was calculated for each sampling interval and then multiplied by the sediment, TP, soluble P, or soluble Al concentrations to determine mass losses of these parameters. Cumulative losses were the sums of the losses for each sampling interval.

Statistics

Statistical analysis was performed using the Statistical Analysis System (SAS, 1996). All variables were tested for normality using the Shapiro-Wilk test with the PROC CAPABILITY procedure. Where results suggested nonnormality, variables were transformed before statistical analyses, with untransformed numbers presented in the text. All data were analyzed using the Mixed Models procedure of SAS with treatment (whole-plot factor) and alum (subplot factor) and their interaction as fixed effects and block as a random effect. Statistical analysis of soil samples also included year and soil depth in the model as fixed effects, analysis of treatment effects was later done as previously described for each year at each depth. Where appropriate, mean separations were carried out using Tukey honestly significant difference with an $\alpha = 0.05$. Statements of statistical significance were based upon $P < 0.05$ unless otherwise stated.

RESULTS

Initial Manure and Soil Characterization

Manure total P ranged from 3.0 to 4.9 g kg^{-1}, WSP ranged from 2.1 to 2.5 g kg^{-1}, total N was approximately 22 g kg^{-1}, and total C ranged from 264 to 342 g kg^{-1}. Compost total P ranged from 1.7 to 3.8 g kg^{-1}, WSP ranged from 0.2 to 0.3 g kg^{-1}, total N ranged from 9 to 15 g kg^{-1}, and total C ranged from 102 to 180 g kg^{-1} (Table 3). The C/N ratio for manure ranged from 12 to 15, whereas the C/N ratio was 12 for the compost. The C/P ratio in the manure ranged from 54 to 113 and was higher than in the compost, which ranged from 32 to 95.

The initial Olsen P concentration of the plots in the spring of 2003 was 3.76 mg kg^{-1}, with a 5% free lime content; therefore, a TP application rate of 78 kg ha^{-1} was recommended for potato production (Idaho Potato Fertilizer Guide, 2008). Manure was applied at 75 kg TP ha^{-1}, whereas actual compost and fertilizer application rates were slightly lower, 63 and 59 kg ha^{-1}, respectively (Table 2). In 2004 and 2005, the Olsen P concentrations were above 13 and 24 mg kg^{-1}, respectively (Fig. 1), and therefore, there was no fertilizer application recommended for production of barley or dry bean during those years. An application rate of approximately 33 Mg ha^{-1} for manure (wet weight) was chosen for 2004 and 2005, which is considerably less than rates typically applied in the region that often exceed 100 Mg ha^{-1} (Oral communication, 2004). This manure application rate translated to a target P application rate of 109 kg ha^{-1} in 2004 and 162 kg ha^{-1} in 2005, which

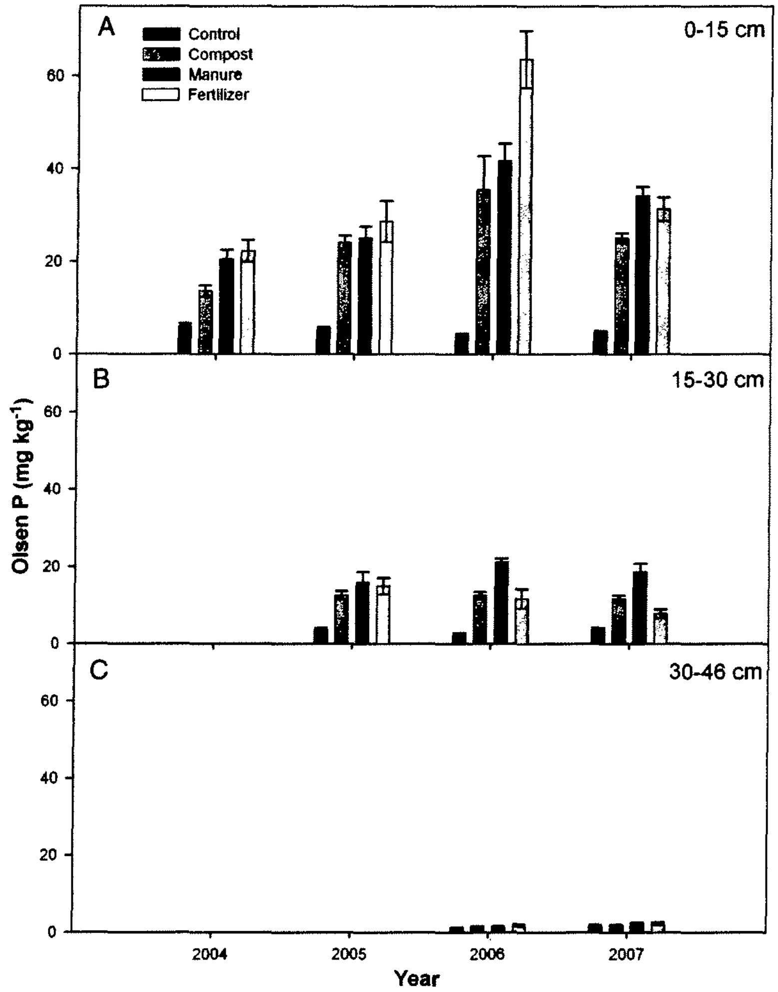

FIG. 1. Bicarbonate (Olsen)-extractable P in soils at (a) 0 to 15 cm, (b) 15 to 30 cm, and (c) 30 to 46 cm for 3 years after treatment application (2004–2006) and 1 year after no P additions (2007). The means of the main plots (averaged across subplots, n = 8) are shown, as there was no significant effect of alum.

although lower than what may typically be land applied in this region was still excessive for plant production.

In 2004, the actual compost application rate was 109 kg TP ha^{-1}, but the actual fertilizer application rate was 47 kg TP ha^{-1} because of an error in application (Table 2). In 2005, the actual compost application rate was 162 kg TP ha^{-1}, whereas the fertilizer was 159 TP kg ha^{-1}. Water-soluble P application rates ranged from 61 to 79 kg ha^{-1} for the manure treatment, 6 to 11 kg ha^{-1} for compost treatment, and 47 to 159 kg ha^{-1} for the MAP treatment. Total N application ranged from 436 to 736 kg ha^{-1} for the manure and compost, whereas the fertilizer N application rate ranged from 23 to 78 kg ha^{-1}. Total C application ranged from 8,421 to 11,109 and 5,259 to 6,551 kg ha^{-1} for the manure and compost treatments, respectively. In 2006, there was no P or N applied to the plots.

Effect of Treatment on Extractable Soil P and Relative Percent Extractable P

There was a significant main effect of treatment, year, and depth; and all interactions were significant ($P < 0.0001$) for both Olsen P and WSP, although there was no significant effect of alum or significant alum interaction terms. As there was no significant effect of alum or significant interaction terms, only the main effects of treatment by year and depth are presented in Figs. 1 and 2. Olsen P concentrations in the 0- to 15-cm depth in control plots decreased over time from 6.0 to 4.7 mg kg^{-1}, whereas the average for the treated plots increased from 19 to 47 mg kg^{-1} from 2004 to 2006 and then decreased to 30 mg kg^{-1} in 2007 (Fig. 1). The WSP concentrations followed the same trend, with a decrease in the 0- to 15-cm depth in the control plots from 4.8 to 3.8 mg kg^{-1} during the 4-year period, whereas the treated plots increased from an average of 12 mg kg^{-1} in 2004 to 28 mg kg^{-1} in 2006 and then decreased to 21 mg kg^{-1} in 2007 (Fig. 2).

In the 0- to 15-cm depth in 2004, both the fertilizer and manure treatments had the highest Olsen P concentrations (not significantly different), followed by the compost that was higher than the control. In 2005, all Olsen P concentrations for the treated plots were not significantly different (average, 26 mg kg^{-1}), but were significantly greater than the control plot (4 mg kg^{-1}) in the 0- to 15-cm depth. In 2006, the fertilizer treatment had the greatest Olsen P concentration in the 0- to 15-cm depth (64 mg kg^{-1}), which was followed by the manure and compost treatments

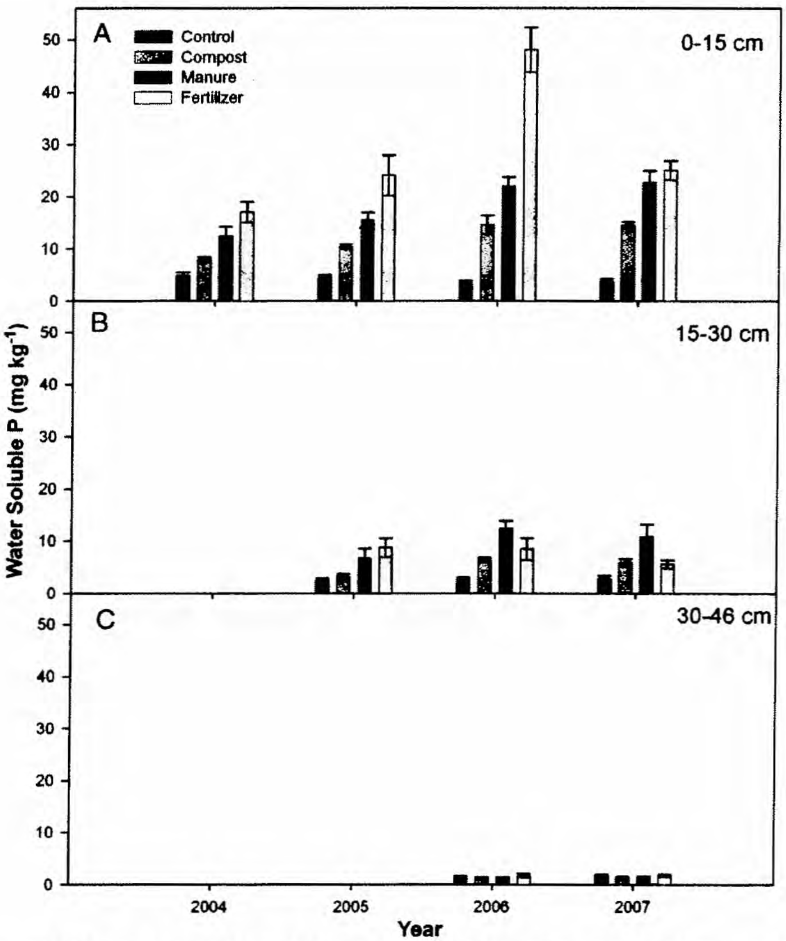

FIG. 2. Water-soluble P in soils at (a) 0 to 15 cm, (b) 15 to 30 cm, and (c) 30 to 46 cm for 3 years after treatment application (2004–2006) and 1 year after no P additions (2007). The means of the main plots (averaged across subplots, n = 8) are shown as there was no significant effect of alum.

(average, 39 mg kg^{-1}), which were not significantly different, whereas the control had the lowest Olsen P concentration (4 mg kg^{-1}). In 2007, with no P applied to the plots the previous year, Olsen P decreased in the 0- to 15-cm increment, with the manure and fertilizer P concentrations being the greatest (average, 33 mg kg^{-1}) followed by the compost (25 mg kg^{-1}) and the control (5 mg kg^{-1}).

The WSP data followed the same general trends as the Olsen P values, with all treatments being significantly greater than the control plots in the 0- to 15-cm soil depth. In 2004 and 2005, the 0- to 15-cm WSP concentrations followed the trend fertilizer > manure > compost > control (Fig. 2). In 2006, the compost and manure treatments were not significantly different but were significantly greater than the control and significantly less than the fertilizer. In 2007, the fertilizer and manure treatments were not significantly different in the 0- to 15-cm soil samples; both were significantly greater than the compost, which was significantly greater than the control.

There was a decrease in both Olsen P and WSP with depth. At the 30- to 46-cm soil depth increment concentrations were less than 2 mg kg^{-1}, and there were no significant differences between treatments. The Olsen P concentration of the control plots at the 15- to 30-cm depth was approximately 4 mg kg^{-1} from 2005 to 2007. The average Olsen P concentrations for the treated plots were 14, 15, and 13 mg kg^{-1} for the 2004, 2005, and 2006 sampling dates, respectively (Fig. 1). The WSP concentrations in the 15- to 30-cm depth averaged approximately 2 mg kg^{-1} for the control plots, whereas the average of the treated plots were 6, 9, and 8 mg kg^{-1} for 2005, 2006, and 2007, respectively. The general trend was higher WSP concentrations in the manure followed by the fertilizer and compost, except in 2005, when the fertilizer and manure were not significantly different (Fig. 2).

There was a significant main effect of treatment, year, and depth, and a significant depth × treatment interaction term for soil TP, with no significant effect of alum or interaction terms. As there was no significant effect of alum or significant interaction terms, only the main effects of treatment by year and depth are presented in Fig. 3. In general, all of the plots receiving P application had greater TP concentrations (average of 787 mg kg^{-1} during 2004–2007) than the control plots (average, 736 mg kg^{-1}) at the 0- to 15- and 15- to 30-cm depths, with few differences among treated plots. At the 30- to 46-cm depth, there were no significant differences between the TP concentrations, which averaged 760 mg kg^{-1} during the 2006 to 2007 period.

As there were unintentional differences in the total amount of P applied to the plots, we calculated a relative percent extractable (RPE) Olsen P and WSP value for the fertilizer,

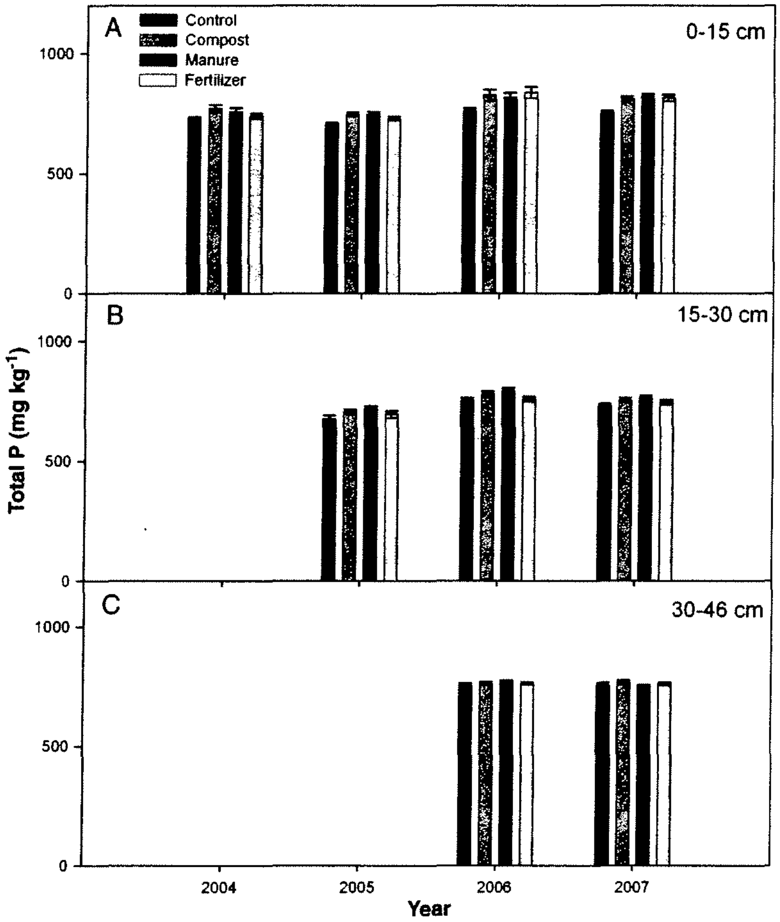

FIG. 3. Total P in soils at (a) 0 to 15 cm, (b) 15 to 30 cm, and (c) 30 to 46 cm for 3 years after treatment application (2004–2006) and 1 year after no P additions (2007). The means of the main plots (averaged across subplots, n = 8) are shown as there was no significant effect of alum.

manure, and compost treatments in the 0- to 15-cm depth for the 2004 to 2006 samples. This calculation gives an indication of the increase in soil test P above the control per unit of P applied and, therefore, illustrates the ability of each treatment to increase soil test P. There was a significant main effect of treatment ($P = 0.02$), whereas the main effects of alum and interaction term were not significant. As there was no significant effect of alum or significant interaction terms, only the main effects of treatment by year and depth are presented in Fig. 4. The RPE Olsen P in 2004 followed the trend fertilizer (116) = manure (80) > compost (51). In 2005, the fertilizer had the greatest RPE Olsen P (207), whereas the manure and compost were not significantly different (average RPE, 74). In 2006, the only difference in RPE Olsen P was between the fertilizer (157) that was significantly greater than the compost (81). The RPE for WSP in 2004 and 2006 followed the trend fertilizer > manure > compost; whereas in 2005, the manure and compost were not significantly different but were significantly lower than the fertilizer. The average RPE WSP values from 2004 to 2006 were 24, 44, and 127 for the compost, manure, and fertilizer treatments, respectively.

Effect of Treatments on Yield, Plant Tissue Concentrations, and P Removal

There was no yield and tissue concentration data for the 2004 potato crop because heavy infestation of Colorado potato beetle destroyed a large portion of the crop. There were no significant main effects of treatment or alum or their interaction for barley yield in 2005, which averaged 264 kg plot^{-1} (Table 4). There was a significant effect of treatment for P harvested per plot ($P = 0.03$), with the compost and manure (932 and 890 g P plot^{-1}, respectively) being significantly greater than the control (638 g P plot^{-1}), whereas the fertilizer treatment (755 g P plot^{-1}) was not significantly different from either of the treatments or the control. There was no main effect of alum on P harvested per plot. There was a significant main effect of treatment but no effect of alum on tissue Ca, Fe, K, Mg, Mn, and P concentrations in the barley. The tissue Ca, Mg, Mn, and P concentrations were all greater for the treated plots than the control but did not significantly differ among treatments. The Fe tissue concentration was greatest in the compost treatment, with all other treatments being the same. The K tissue concentrations for the compost and manure treatments were not significantly different but were significantly greater than that of the control treatment, whereas the fertilizer tissue concentration was not significantly different from either that of the manure or the control treatment.

There was a significant main effect of treatment on bean yield ($P = 0.05$) and P harvested per plot ($P = 0.002$) in 2006 but no effect of alum. Both the yield and P harvested per plot were significantly greater in the treatment plots (averages, 77 kg plot^{-1}

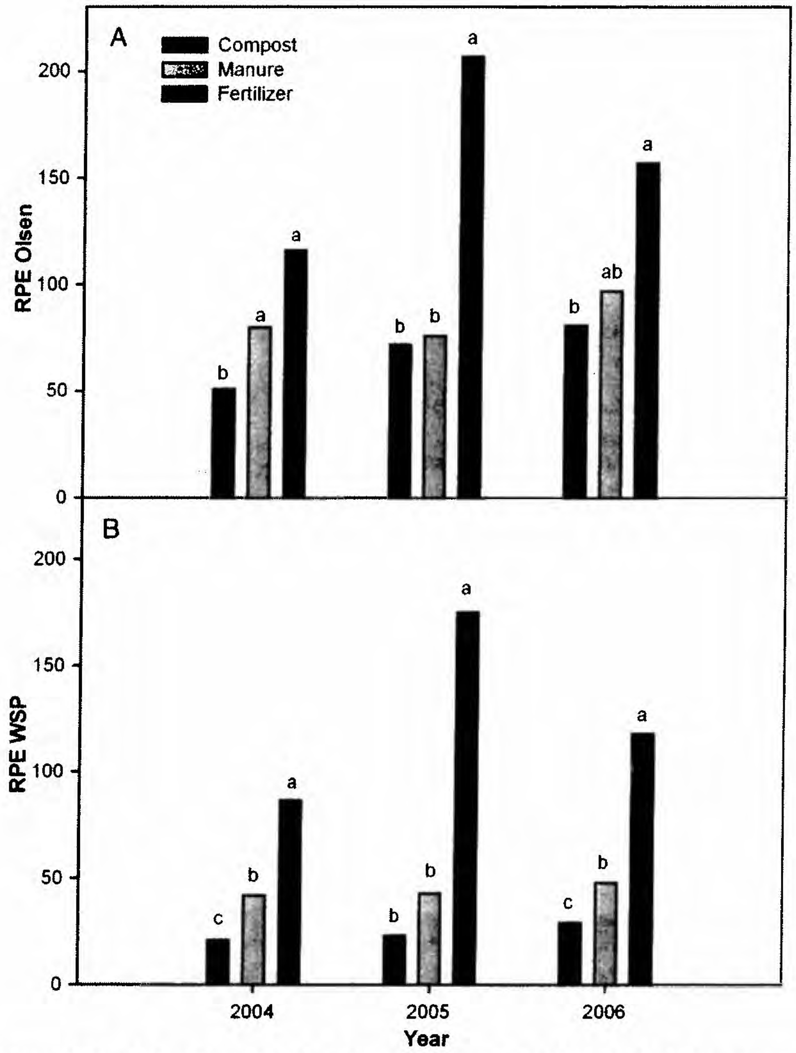

FIG. 4. The RPE Olsen P (a) and WSP (b) for soils collected at 0- to 15-cm depth in 2004 to 2006. The means of the main plots (averaged across subplots, n = 8) are shown as there was no significant effect of alum.

TABLE 4. Yield and Plant Tissue Concentrations for Crops Grown in 2005 (Barley) and 2006 (Beans)

	Yield	P out	Ca	Fe	K	Mg	Mn	P
	kg Plot^{-1}	g Plot^{-1}	mg kg^{-1}					
Barley								
Control	265 (11)	638 (54) b	518 (9) b	45 (1) b	5542 (78) c	1241 (17) b	22 (0.3) b	2384 (120) b
Compost	288 (30)	932 (30) a	601 (22) a	52 (2) a	6395 (215) a	1375 (25) a	24 (0.5) a	3252 (125) a
Manure	261 (18)	890 (63) a	584 (4) a	47 (1) b	6194 (45) ab	1362 (8) a	23 (0.6) a	3411 (36) a
Fertilizer	240 (18)	755 (63) ab	589 (12) a	48 (1) b	5858 (132) bc	1368 (19) a	23 (0.7) a	3132 (57) a
Beans								
Control	67 (6) b[†]	227 (20) b	1564 (56) a	59 (3)	14,850 (242) b	1463 (20) b	17 (0.4) a	3430 (167) b
Compost	76 (5) a	328 (22) a	1365 (48) b	62 (2)	16,695 (208) a	1508 (18) ab	16 (0.2) b	4300 (51) a
Manure	76 (7) a	333 (30) a	1373 (32) b	64 (6)	17,251 (143) a	1526 (8) a	16 (0.3) b	4370 (56) a
Fertilizer	78 (5) a	342 (17) a	1500 (25) a	66 (2)	15,486 (274) b	1541 (19) a	16 (0.2) b	4381 (69) a

The means of the main plots (averaged across subplots, n = 8) are shown as there was no significant effect of alum.

[†] Within columns for each crop, means followed by the same letter are not significantly different at $\alpha = 0.05$.

Ca: total calcium; Fe: total iron; K: total potassium; Mg: total magnesium; Mn: total manganese; P: total P.

and 334 g P plot^{-1}, respectively) than the control (67 kg plot^{-1} and 227 g P plot^{-1}, respectively), with no differences between treatments (Table 4). There was a significant main effect of treatment on Ca, K, Mg, Mn, and P tissue concentrations but no effect of alum. The Ca tissue concentrations were greatest in the control and fertilizer treatments, whereas the manure and compost tissue concentrations were lower and not significantly different. The K tissue concentrations were greatest in the compost and manure treatments and lower in the fertilizer and control treatments. Tissue Mg concentrations were greater in the manure and fertilizer treatments than the control, whereas the Mn concentrations were greater in the control than the fertilized plots, which did not differ.

Effect of Treatments on Runoff Losses of P and Al

There were no significant differences in the inflow water data for the seven irrigations monitored in this study (data not shown). In 2004, the first three irrigations were monitored with the cumulative losses of TP, soluble P, and soluble Al presented in Table 5. Total P loss was linearly correlated to total sediment loss, with an $r^2 = 0.86$ (data not shown). There was no significant main effect of either treatment or alum on TP or soluble Al lost from the furrows for any of the three irrigations. There was no main effect of treatment or alum on soluble P during the first two irrigations in 2004, but there was a significant main effect of treatment during the third irrigation event in this year but no main effect of alum addition. The soluble P lost from the furrows during the third irrigation followed the trend fertilizer = manure > compost > control. This same trend occurred in the first irrigation event of this year, which approached significance ($P = 0.08$).

There was no main effect of treatment or alum on the cumulative losses of TP, soluble P, and soluble Al during the two irrigations monitored in 2005 (Table 6). Total P losses were less during 2005 irrigations (average, <500) than in 2004 (average, >2,000) or 2006 (average, >10,000) as the barley decreased the amount of sediment lost. There was a positive linear correlation between sediment lost and TP lost in the 2005 irrigations, with an $r^2 = 0.78$ (data not shown). The TP lost from the furrows in 2006 was not affected by treatment or alum in the first irrigation event, but there was a main effect of alum for the second irrigation, with the alum treatment having less TP lost versus no alum addition (Table 7). There was a main effect of treatment on soluble P lost from the first but not the second irrigation event in 2006, with no effect of alum for either irrigation. The soluble P lost from the manure and fertilizer plots was greater than the control, whereas the compost did not significantly differ from the other treatments or the control.

TABLE 5. Cumulative Runoff of Total P, Soluble P, and Soluble Al From the Three Irrigations in 2004

	Cumulative Runoff, mg		
	Total P	**Soluble P**	**Soluble Al**
Irrigation 04-1			
Control	5962	96	82
Compost	4312	111	82
Manure	5894	160	107
Fertilizer	6682	168	118
Alum	6143	139	105
No alum	5282	129	90
Treatment	**0.74**	**0.08**	**0.43**
Alum	**0.40**	**0.30**	**0.13**
Treatment*Alum	**0.17**	**0.18**	**0.32**
Irrigation 04-2			
Control	7970	96	76
Compost	4588	107	70
Manure	5434	158	96
Fertilizer	6532	174	106
Alum	6155	134	94
No alum	6107	134	79
Treatment	**0.72**	**0.21**	**0.57**
Alum	**0.71**	**0.97**	**0.71**
Treatment*Alum	**0.96**	**0.65**	**0.81**
Irrigation 04-3			
Control	7950	119 c[†]	71
Compost	6816	142 b	86
Manure	9388	194 a	120
Fertilizer	10,685	193 a	108
Alum	9613	163	101
No alum	7806	161	92
Treatment	**0.43**	**0.02**	**0.13**
Alum	**0.76**	**0.08**	**0.69**
Treatment*Alum	**0.90**	**0.08**	**0.08**

Means of the main effects for treatment (compost, manure, fertilizer, and control, n = 8) and alum (alum: alum-treated plots; no alum: no alum treatment, n = 16) are shown.

[†] Within columns for each irrigation, means followed by the same letter are not significantly different at $\alpha = 0.05$.

TABLE 6. Cumulative Runoff of Total P, Soluble P, and Soluble Al From the Two Irrigations in 2005

	Cumulative Runoff, mg		
	Total P	**Soluble P**	**Soluble Al**
Irrigation 05-1			
Control	363	144	59
Compost	307	136	49
Manure	567	240	65
Fertilizer	688	198	78
Alum	516	175	61
No alum	446	184	64
Treatment	**0.45**	**0.14**	**0.75**
Alum	**0.14**	**0.53**	**0.62**
Treatment*Alum	**0.79**	**0.08**	**0.10**
Irrigation 05-2			
Control	337	177	63
Compost	353	177	57
Manure	387	211	51
Fertilizer	550	174	51
Alum	429	185	55
No alum	384	184	55
Treatment	**0.53**	**0.76**	**0.84**
Alum	**0.53**	**0.97**	**0.97**
Treatment* Alum	**0.52**	**0.96**	**0.19**

Means of the main effects for treatment (compost, manure, fertilizer, and control, n = 8) and alum (alum: alum-treated plots; no alum: no alum treatment, n = 16) and alum are shown.

TABLE 7. Cumulative Runoff of Total P, Soluble P, and Soluble Al From the Two Irrigations in 2006

	Cumulative Runoff, mg		
	Total P	**Soluble P**	**Soluble Al**
Irrigation 06-1			
Control	9940	87 b	196
Compost	13,608	132 ab	209
Manure	15,315	162 a	166
Fertilizer	12,571	197 a	195
Alum	11,042	140	162
No alum	14,674	149	221
Treatment	**0.80**	**0.05**	**0.81**
Alum	**0.18**	**0.56**	**0.08**
Treatment*Alum	**0.47**	**0.85**	**0.86**
Irrigation 06-2			
Control	14,735	70	171
Compost	14,105	112	157
Manure	10,770	137	131
Fertilizer	11,155	154	144
Alum	11,480 b[†]	118	145
No alum	13,903 a	118	157
Treatment	**0.56**	**0.13**	**0.53**
Alum	**0.05**	**0.97**	**0.43**
Treatment*Alum	**0.27**	**0.97**	**0.45**

Means of the main effects for treatment (compost, manure, fertilizer, and control, n = 8) and alum (alum: alum-treated plots; no alum: no alum treatment, n = 16) and alum are shown.

[†] Within columns for each irrigation, means followed by the same letter are not significantly different at $\alpha = 0.05$.

There was no effect of treatment or alum on soluble Al lost during either irrigation event in 2006. There was a positive linear correlation between sediment lost and TP lost, with an $r^2 = 0.80$ (data not shown).

DISCUSSION

The surface application of alum to land-applied manures before incorporation had no effect on extractable soil P or soluble P losses from furrow irrigation. In one of the seven monitored irrigation events, the TP lost from alum-treated plots was less than plots without alum treatment, but the lack of consistency implies that it is not a reliable treatment when used in this manner. Although the addition of alum or alum-based water treatment residuals to dairy manure was shown to reduce soluble P by up to 99% (Dou et al., 2003; Meals et al., 2008), the surface application of alum to land-applied manures, which were then incorporated by disking, did not seem to have the same effect, which is most likely caused by a lack of thorough mixing of the manure and alum and possibly caused by a lack of moisture because the manures and compost material tend to be fairly dry.

Other studies have shown decreases of 50% to 84% in soluble P losses during simulated rainfall when alum-treated manures have been applied to soils (Smith et al., 2001; Smith et al., 2004; DeLaune et al., 2006; Sistani et al., 2006), which again may be more effective because there was better incorporation of the alum treatment with the manure before land application. In addition, these treated manures were surface applied to plots, therefore increasing the interaction between manure and runoff water, which could have enhanced the effects of alum treatment of the manures. There are also systematic differences between furrow irrigation and simulated rainfall. Water flowed in the irrigation furrows for 7 to 10 h during the seven monitored irrigations. During an irrigation event, sediment is detached and deposited within the furrow. Water flowing in irrigation furrows only interacts with a small portion of the soil surface within a plot (<10%) compared with sheet flow over much of plot surface during a rainfall simulation. This decreased contact between runoff water and treated soil could explain why there were no differences in soluble P losses with alum treatment seen in this study, although other studies have shown significant effects.

There were main effects of treatment on soil-extractable P. Both Olsen P and WSP were greater in the surface soils (0–15 cm) in treated versus control plots. Olsen P concentrations were greatest in either the fertilizer or manure treatments in 2004, 2006, and 2007, although in 2005, there were no differences among treatments. It is interesting to note that in 2005, although half of the amount of fertilizer was applied compared with the compost and manure treatments, the Olsen P concentration was just as high, indicating that fertilizer P has a greater potential to raise Olsen P than manure or compost. If we examine the RPE Olsen values, the fertilizer always had the highest value, although this was not significantly greater than that of the manure in 2 of the 3 years but was always significantly greater than that of the compost. Leytem and Westermann (2005) also reported that applications of fertilizer (MAP) to calcareous soils increased Olsen P concentrations greater than either beef cattle manure or dairy compost. Kashem et al. (2004) also reported that additions of cattle manure to calcareous soils increased Olsen P concentrations less than addition of MAP.

Olsen P concentrations in the 15- to 30-cm depth were greater for the treated versus control plots each year. There were no differences in the treated plots in 2005, but in 2006 and 2007, the manure treatment had the highest Olsen P concentrations, suggesting more downward movement of P from the manured soils compared with the compost and fertilizer treatments. Eghball et al. (1996) reported that P from cattle manure applied to calcareous soils under irrigation had deeper soil movement than similar P application rates of fertilizer. They attributed this enhanced movement of P to chemical reactions of P occurring with compounds in the manure, which may have enhanced P solubility.

The differences in WSP concentrations were more pronounced than Olsen P differences. In the surface soils, the fertilizer treatment had the greatest WSP concentration for the 3 years that followed treatment application. In 2 of the 3 years after treatment application, the manure treatment WSP concentrations were greater than the compost treatment concentrations. As the soluble P concentrations in the manure were greater than in the compost, this is not an unexpected result. As with the Olsen P concentrations, there appeared to be greater downward movement of WSP in the manure treatments as the 15- to 30-cm soil depth in 2006 and 2007 had greater WSP than the other treatments. The RPE WSP values were consistently greatest for the fertilizer treatments, indicating that addition of fertilizer had a greater ability to raise soil WSP concentrations than addition of either manure or compost. In 2 of the 3 years, the RPE WSP was greater in the manure treatment than that in the compost treatment; although in 2005, the two treatments were not significantly different. Again, this difference in RPE WSP between manure and compost is likely caused by the differences in the P solubility of the two materials. Leytem and Westermann (2005) also reported that increases in WSP were greater for calcareous soils treated with fertilizer versus manure or composted manures. Kashem et al. (2004) also reported that WSP in soils treated with MAP was greater than in soils treated with cattle manure.

Although there were treatment effects on soil-extractable P, there were no differences in yield or P harvested in either 2005 or 2006. This lack of response to differences in soil test P value is likely because the soils were sufficient in P for crop production, and therefore, there was no plant response. Leytem and Westermann (2005) also reported that both shoot biomass and shoot P accumulation in barley were similar when soils were amended with MAP, manures, or composts. One notable difference in plant tissue concentrations was the increase in K tissue concentrations in the manure and compost treatments. As both manure and compost can have high salt concentrations, this translated into higher K tissue concentrations. At low application rates, this may not be a problem, but high application rates of compost or manure to land before forage crop production could have the potential to negatively impact forage quality because of high K uptake.

The differences in WSP concentrations did not consistently translate to differences in soluble P losses from the plots with irrigation. In 2004, there was a significant treatment effect on soluble P lost, with manure and fertilizer having the greatest losses followed by the compost with the control having the lowest losses. This same numeric trend was seen during the other two irrigations in 2004 and approached significance in the first irrigation event but was insignificant in the second event. During the first irrigation event in 2006, there again was a significant effect of treatment, with the fertilizer and manure having greater soluble losses than the control, but they were not different from the compost treatment, which was also not different from that of the control. The same numeric trend is seen in the second irrigation event, which again approached significance. High variability of soluble P lost from the furrows prevented treatment differences from being significant in many cases, if there was greater replication of treatments, then the statistical power would have been greater, and these differences may have been significant. Gilley and Eghball (2002) examined the effects of compost and fertilizer application to calcareous soils on P runoff and found that total amounts of P in runoff were similar between the two treatments and that soluble P concentrations in the soils did not correlate well with P losses.

CONCLUSIONS

The surface application of alum to land-applied manures before incorporation was not a good management practice to stabilize P in this study. There are differences in the ability of fertilizer, manure, and compost to alter soluble P in soils and potentially alter the soluble P lost during furrow irrigation. Fertilizer addition had the greatest potential to increase soluble P in soils, which translated to greater soluble P losses with irrigation in some instances. Manure addition raised soil WSP to a lesser extent than fertilizer addition but had a similar effect on Olsen P. Manure application tended to have the same effect on soluble P losses from furrow-irrigated fields as fertilizer. The addition of compost to soils tended to increase both Olsen P and WSP less than addition of manure or fertilizer and translated into equivalent or lower losses of soluble P during furrow irrigation. As the addition of similar amounts of TP in fertilizer, manure, and compost can translate into differences in soil soluble P and soluble P losses from furrow-irrigated fields, care should be taken when applying these materials to account for these differences and apply in a manner to reduce the risk of P losses from irrigated fields.

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