Phosphate Availability and Inorganic Transformation in an Alum Sludge-Affected Soil

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ABSTRACT

Land application of alum sludge is a disposal alternative. A greenhouse experiment was conducted to determine (i) alum sludge effects on phosphorus (P) availability and inorganic P forms, and (ii) the relationship between inorganic P fractions and P availability. Alum sludge slurry (0, 4.45, 8.9, and 17.8 g solid kg^{-1} soil) was surface applied to wheat (*Triticum aestivum* L.) grown in aYauhannah soil (fine-loamy, siliceous, thermic Aquic Hapludults) at four P rates (0, 6.5, 11, and 22 mg kg^{-1} soil). After the first wheat crop, the sludge was mixed throughout the soil and a second crop grown. Surface-applied sludge decreased wheat dry matter (DM) and P uptake. When incorporated, 4.45 g kg^{-1} alum decreased DM and P uptake. Phosphate application increased DM and P uptake of the first wheat crop, but had no effect on the second crop. Surface-applied sludge increased Al-P, Fe-P, and Ca-P in the 0- to 7.5-cm soil depth, but not in the 7.5- to 15-cm soil depth. Loosely bound-P and Al-P increased with P rate. Phosphorus uptake and DM of the first wheat crop were positively related to loosely bound-P and Mehlich 1-P. Dry matter of the second wheat crop was positively related to loosely bound-P and Mehlich 1-P and P uptake was positively related to loosely bound-P. Aluminum-P was negatively related to P availability indices. In alum sludge-affected soils applied P is immobilized mainly as Al-P, and Mehlich 1-P and loosely bound-P are reliable estimators of P availability.

SLUDGES produced in the purification of drinking water using flocculants such as alum ($Al_2(SO_4)_3\,14H_2O$) and ferric chloride ($FeCl_3$) are unsuitable for landfill disposal, since they have a low (1–2%) solids content. Current landfill regulations require that sludges contain at least 20% solids, but in this condition, these water treatment sludges (WTS) are difficult to handle. Application of WTS to agricultural land has also been considered a disposal option. The suitability of WTS for land application will be determined by its composition and subsequent effects on soil chemical and physical properties.

Although heavy metals and pathogens are major concerns dictating suitability of most municipal wastes for land application, WTS do not pose these hazards (Cox, A.E. 1993. Effect of alum sludge application on phosphate and metal chemistry in an Atlantic Coastal Plain soil. M.S. thesis. Clemson Univ., Clemson, SC.; Elliott et al., 1990; Elliott and Singer, 1988). Phosphate (P) retention is likely the predominant factor limiting the application of WTS (Heil and Barbarick, 1989; Grabareck and Krug, 1987; Bugbee and Frink, 1985; Rengasamy et al., 1980) which contain relatively high amounts of hydrous oxides of aluminum and iron. In soil, these compounds provide enormous reactive surface area with considerable capacities to "fix" P (Hamad et al., 1992; Loganathan et al., 1987) and make it unavailable to plants. Heil and Barbarick (1989) observed that alum sludge rates up to 10 g kg^{-1} increased plant yield, but higher rates decreased yield. The decrease in growth at higher rates was probably due to P "fixation" by the alum sludge. Results of leaf tissue analysis have also shown that P was less available to plants grown in alum sludge-amended soil (Bugbee and Frink, 1985) and iron sludge-amended media (Elliott and Singer, 1988). Bugbee and Frink (1985) found that doubling the conventional P fertilization rate of lettuce (*Lactuca sativa* L.) cannot overcome P deficiencies caused by addition of dried alum sludge. However, Lucas et al. (1994) showed that P deficiency in fescue (*Festuca arundinaceae*) caused by application of 40 g kg^{-1} alum sludge to an Ultisol could be overcome by doubling the recommended P fertilization rate. Geertsema et al. (1994) found no long-term (30 months) effects of alum sludge application on plant-available P or loblolly pine (*Pinus rigida*) growth in a Coastal Plain sandy loam.

The components of WTS may affect the relative abundance of inorganic forms of P in soils and, subsequently influence P availability. If WTS are to be used as a soil amendment, the relationships between P retention, changes in forms of soil P, and estimates of P availability need to be determined. This information will help in developing P management guidelines for WTS-affected soils. Inorganic P fractionation procedures have been used to estimate the fate of applied P and the relationship between forms of P and plant P nutrition (Chang et al., 1983; Ryan et al., 1985; Furlani et al., 1987). Chang et al. (1983) found that application of sewage sludges increased soluble P and Al- and Fe-bound P. Others have shown that application of WTS reduced Morgan soil test P (Bugbee and Frink, 1985), equilibrium phosphate concentration (EPC), and Bray 1 soil test P (Dempsey et al., 1990). However, the changes in inorganic forms of soil P associated with WTS application have not been reported.

The objectives of this study were to determine (i) the effect of alum sludge amendment on P availability and inorganic forms of P in an acid soil and (ii) the relationship between inorganic P fractions and P availability.

MATERIALS AND METHODS

Soil and Sludge Characterization

The surface (0–15 cm) of a Yauhannah soil was collected from a proposed alum sludge land application site in South Carolina. Alum sludge (2% solids) was obtained from the Bull Creek water treatment plant near Conway, SC. Characteristics of the soil and sludge are presented in Table 1. Total sludge solids were determined after drying the slurry at 65°C. Total elemental composition of the soil and sludge was done

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Published in J. Environ. Qual. 26:1393–1398 (1997).

Abbreviations: DM, dry matter; WTS, water treatment sludges; ANOVA, analysis of variance; EPC, equilibrium phosphate concentration.

Table 1. Total elemental analysis, pH, Mehlich 1-P, and exchangeable Al of Yauhanah soil and alum sludge.

Material	Al	Fe	Ca	P	pH	Mehlich 1-P	Exchangeable Al‡
	%					mg kg^{-1}	cmol kg^{-1}
Soil	0.41	0.35	0.24	0.03	4.4	63.2	0.33
Alum sludge†	4.79	1.28	0.04	0.24	5.1	37.2	0.30

† All analyses except pH were performed on oven-dried sludge.
‡ 1 *M* KCl-exchangeable.

after fusion of each material with Na_2CO_3 (Lim and Jackson, 1982). Exchangeable Al was estimated by 1 *M* KCl extraction (Barnishel and Bertsch, 1982). Available P was estimated by Mehlich 1 (0.05 *N* HCl/0.025 *N* H_2SO_4) extraction (Olsen and Sommers, 1982). Phosphorus was determined by the method of Murphy and Riley (1962). Potassium was determined by flame emission and other metals by atomic absorption spectrophotometry. Soil pH was measured in a 1:1 soil/water suspension. The pH of the sludge was measured in the liquid slurry.

Greenhouse Experiment

Soil was sieved through a 1-cm mesh and amended at 10 mg N kg^{-1} soil as NH_4NO_3 and at 88 mg K kg^{-1} soil as KCl. Four P treatments; 0, 6.5, 11, and 22 mg P kg^{-1} were applied as KH_2PO_4. All nutrient additions were made via solutions, mixed thoroughly in 2.25 kg soil, and placed in 2.5-kg pots lined with polyethylene bags. The pots were placed on the greenhouse bench in a split plot arrangement (sludge rate as the main treatment and P rate as the split treatment) with three replications, watered to about 80% field capacity (0.22 kg kg^{-1}), then covered and left to equilibrate for 7 d. Crop I wheat (cv. Atlas 66) was seeded in February 1991 at 10 seeds per pot and thinned to six plants per pot at the two-leaf stage.

At the two-leaf stage, alum sludge treatments were initiated by irrigating with either deionized water (0 treatment), one of two sludge/deionized water mixtures (3:1 and 1:1), or undiluted sludge. During the first 3 wk of sludge application, the surface of the pots was disturbed twice weekly to a depth of 2.5 cm to minimize "caking" and to facilitate incorporation of the sludge solids. Soil moisture was maintained at 60 to 80% field capacity. This was done by weighing pots daily before irrigation to estimate a mean amount of irrigation required to attain 80% field capacity. After 4 wk, alum sludge application was terminated establishing sludge rates of 0, 4.45, 8.9, and 17.8 g solid kg^{-1} soil. Hereafter, all pots were irrigated with deionized water. The N application (NH_4NO_3 solution) was repeated every 14 d. Throughout the growing period, the temperature range in the greenhouse was 23 to 27°C.

Plants were clipped at the soil surface 50 d after seeding, dried, weighed, and ground to pass through a 0.1-mm sieve. Soil samples were taken from the top (0–7.5 cm) and the bottom (7.5–15 cm) of each pot. The pots were left to air dry for 14 d, then covered in place with polyethylene bags prior to reseeding for crop II wheat.

In November 1992, the soil in each pot was sieved to remove roots, thoroughly mixed and 1.5 kg retained. Nitrogen (100 mg N kg^{-1} soil) and potassium (88 mg K kg^{-1} soil) were applied in nutrient solution to each batch of soil as previously described. Some plants in the first wheat crop showed signs of N deficiency, so the N application to the second wheat crop was increased. The N application was repeated every 14 d. The soil was placed in 2-kg pots lined with polyethylene bags. The pots were arranged on the bench and watered with deionized water, as described for the first wheat crop, and left to equilibrate for 7 d. Wheat was seeded at six seeds per pot, then thinned to four plants per pot at the two-leaf stage. Throughout the experiment, all pots were irrigated with deionized water. Throughout the growing period, the temperature range in the greenhouse was 16 to 20°C.

At 50 d after seeding, plant tops were harvested, and a soil sample, representative of the whole pot (0–15 cm) was obtained.

Plant and Soil Analyses

Duplicate subsamples of plant tissue were digested using a nitric-perchloric acid mixture (Gange and Page, 1974) and P determined using the Murphy and Riley (1962) method.

Soil samples were air-dried and sieved to pass through a 2-mm sieve. Extractable P was determined by the Mehlich 1 method (Olsen and Sommers, 1982). Inorganic forms of P were estimated using a sequential scheme (Chang and Jackson,

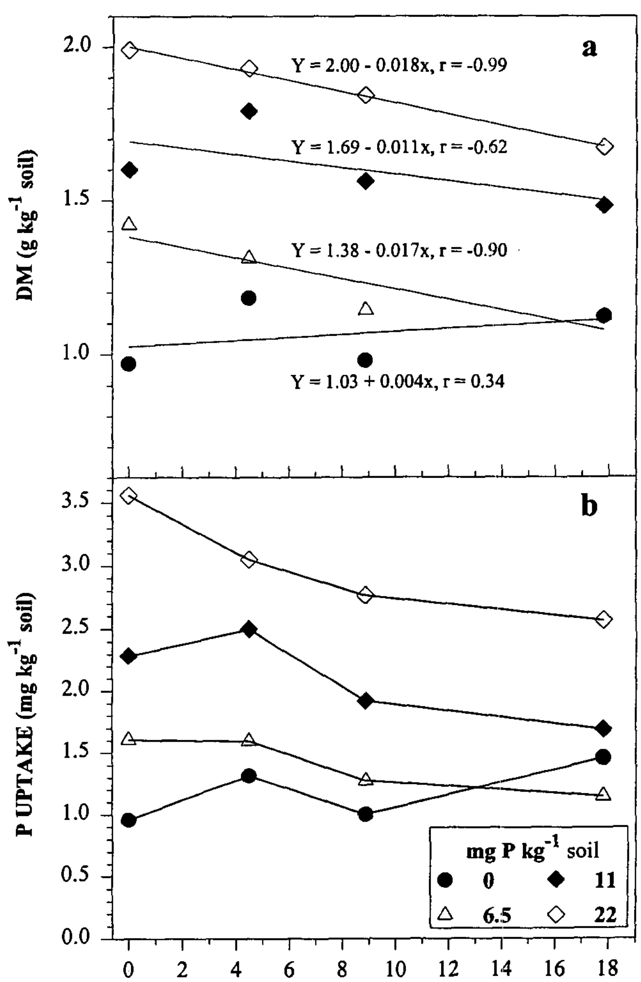

Fig. 1. Effect of alum sludge application and P fertilization on (*a*) DM and (*b*) P uptake of the first wheat crop.

1957) modified by Petersen and Corey (1966), except that residual P was not extracted. One gram of soil was sequentially extracted with 50 mL each of 1 *M* NH_4Cl (loosely bound-P), 0.5 *M* NH_4F (aluminum-P), 0.1 *M* NaOH (iron-P), 0.3 *M* $Na_3(C_6H_5O_7)\,2H_2O$ + 1 g sodium dithionite (occluded-P), and 0.5 *M* H_2SO_4 (calcium-P). The soil was washed twice between each extraction step by suspending in 25 mL of saturated NaCl solution and centrifuged to remove the entrained solution of the previous step. Phosphorus in the NH_4F extract was determined as described by Chang and Jackson (1957) and occluded-P by inductively coupled plasma spectroscopy. Phosphorus was determined in all other extracts by the Murphy and Riley (1962) method. All analyses were done in duplicate.

Analysis of variance (ANOVA) was conducted using SAS (SAS, 1985). Orthogonal polynomial contrasts were used to determine the effects of treatment levels on response variables. Simple correlation analysis was done between variables in which main effects or sludge rate × P rate interactions were significant to evaluate the relationship between estimates of P availability and inorganic forms of P.

RESULTS

Plant Growth and Phosphorus Uptake

Surface application of alum sludge decreased the growth of the first wheat crop in all P treatments, except the zero P treatment (Fig. 1a). The sludge treatments applied to the first wheat crop and then incorporated into the entire soil mass prior to the second wheat crop also decreased DM (Fig. 2). At the 4.45 g kg^{-1} sludge rate, DM was 46% of the zero sludge treatment. Higher sludge application rates resulted in a slightly further decrease in DM.

Phosphorus uptake by the first wheat crop was not significantly affected by sludge application (Fig. 1b) but tended to increase with sludge rate in the zero P treatment and tended to decrease where P was applied. Phosphorus uptake in crop II wheat decreased considerably at the 4.45 g kg^{-1} sludge rate (Fig. 2b), but little additional decrease occurred at higher sludge rates.

Phosphate fertilization caused a linear increase in DM and P uptake by the first wheat crop (Fig. 1). There was a significant P rate × sludge rate effect on DM. As

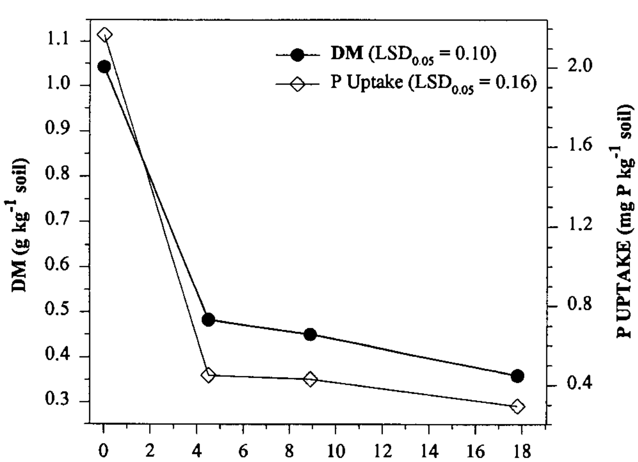

Fig. 2. Effect of alum sludge application on DM and P uptake of the second wheat crop.

sludge rate increased, the effect of added P decreased. Dry matter in the zero sludge treatment increased from 0.97 g kg^{-1} where no P was added to 2.0 g kg^{-1} at the highest P rate. However, in the highest sludge treatment, DM increased from 1.1 g kg^{-1} where no P was added to only 1.7 g kg^{-1} in the highest P rate. There was no residual effect of P fertilization on either DM or P uptake by the second wheat crop.

Soil Phosphorus Pools

Alum sludge application significantly decreased Mehlich 1-P after each wheat crop (Table 2). Mehlich 1-P in the 0- to 7.5-cm soil depth after the first wheat crop decreased linearly with sludge rate, but P in the 7.5- to 15-cm depth was unaffected by the sludge. Mehlich 1-P of the entire soil volume was also decreased by sludge rate after the second wheat crop. Phosphorus fertilization rate increased Mehlich 1-P linearly in both 0- to 7.5-cm and 7.5- to 15-cm depths after the first wheat crop, but there was no residual effect of P fertilization on Mehlich 1-P after the second wheat crop.

Loosely bound-P, that extracted with 1 *M* NH_4Cl, decreased linearly with sludge rate in the 0- to 7.5-cm depth (Table 3). In the 7.5- to 15-cm depth, loosely bound P was unaffected by sludge treatment. Loosely bound-P increased with P rate in both depths and was higher in the 7.5- to 15-cm depth. Loosely bound-P decreased with sludge rate after the second wheat crop, but was unaffected by P rate (Table 4).

Aluminum-P, Fe-P, and Ca-P in the 0- to 7.5-cm depth increased with sludge rate after the first wheat crop, but there was no sludge effect in the 7.5- to 15-cm depth (Table 3). Aluminum-P increased with P rate in both depths. The P effect was greater in the 7.5- to 15-cm

Table 2. Effect of surface-applied alum sludge and P fertilization on Mehlich 1-P after the first and second wheat crops.

P rate	Sludge rate	After first wheat: 0- to 7.5-cm depth	After first wheat: 7.5- to 15-cm depth	After second wheat: 0- to 15-cm depth
mg kg^{-1} soil	g kg^{-1} soil	mg P kg^{-1} soil		
0	0	70.7	64.7	68.3
	4.45	66.6	64.9	65.5
	8.9	64.3	65.6	65.2
	17.8	61.5	65.2	62.7
6.5	0	69.7	66.9	69.2
	4.45	68.7	68.2	65.5
	8.9	67.0	69.4	64.9
	17.8	61.1	66.3	62.3
11	0	72.8	70.4	70.2
	4.45	70.8	69.0	69.0
	8.9	66.7	71.1	69.0
	17.8	60.0	64.3	66.6
22	0	75.1	72.9	72.1
	4.45	71.1	72.7	68.4
	8.9	71.5	69.0	72.4
	17.8	65.7	74.6	70.6
	P	**	*	NS†
	Sludge	**	NS	**
	P × Sludge	NS	*	NS

*,** ANOVA significant at the 0.01 and 0.05 probability levels, respectively.
† NS = not significant.

Table 3. Effect of surface-applied alum sludge and P fertilization on soil P fractions at two soil depths after the first wheat crop.

		0- to 7.5-cm depth				7.5- to 15-cm depth			
P rate	Sludge rate	LB-P†	Al-P	Fe-P	Ca-P	LB-P†	Al-P	Fe-P	Ca-P
mg kg^{-1} soil	g kg^{-1} soil	mg P kg^{-1}							
0	0	5.5	94.3	51.1	18.6	7.9	102.4	63.5	21.2
	4.45	3.3	105.4	61.9	18.2	7.9	104.6	56.0	22.4
	8.9	2.7	111.4	77.8	23.9	8.2	104.5	56.7	15.0
	17.8	2.0	113.0	81.2	23.8	6.1	103.5	56.1	22.5
6.5	0	6.0	96.4	50.5	16.3	8.2	103.0	57.5	18.9
	4.45	4.0	106.8	61.2	20.5	8.4	106.3	56.0	23.8
	8.9	2.5	112.8	71.4	20.6	8.3	109.8	64.0	16.4
	17.8	2.1	114.0	85.5	26.0	7.3	108.2	56.8	18.9
11	0	5.9	102.3	53.7	18.4	9.5	113.2	60.8	17.9
	4.45	4.4	110.0	64.5	21.2	9.0	110.8	57.2	19.9
	8.9	3.0	114.2	68.7	20.2	8.9	115.4	58.0	16.8
	17.8	2.3	136.9	79.4	21.2	6.8	111.2	57.2	20.6
22	0	6.9	106.2	53.7	20.1	9.7	114.6	57.8	20.2
	4.45	4.8	111.6	61.4	19.7	9.7	116.6	59.1	16.5
	8.9	3.8	118.5	71.3	21.4	9.7	116.0	56.8	20.4
	17.8	2.3	130.2	90.8	23.5	8.2	120.9	55.6	24.5
	P	**	*	NS‡	NS	**	**	NS	NS
	Sludge	**	**	**	*	NS	NS	NS	NS
	P × Sludge	NS	NS	NS	NS	NS	NS	NS	NS

*,** ANOVA significant at the 0.01 and 0.05 probability levels, respectively.
† Loosely bound-P.
‡ NS = not significant.

depth {Al-P (mg kg^{-1}) = 103.9 + 0.62 P (mg kg^{-1}), r = 0.98**} than in the 0- to 7.5-cm depth {Al-P (mg kg^{-1}) = 106.4 + 0.53 P (mg kg^{-1}), r = 0.88*}.

After the sludge was mixed with the entire soil volume, and the second wheat crop was grown, Fe-P increased with sludge rate (Table 4), but Al-P was not significantly affected. Phosphorus fertilization increased Al-P {Al-P (mg kg^{-1}) = 111.43 + 0.57 × P (g kg^{-1}), r = 0.93*}. No other soil-P fractions were affected by applied P.

Relationship between Phosphorus Fractions and Phosphorus Availability

Dry matter and P uptake of the first wheat crop were positively related to loosely bound-P and Mehlich 1-P of the entire soil volume (Table 5). Phosphate uptake was also related to Al-P and Fe-P of the entire soil volume, but not as well as its relationship to loosely bound-P and Mehlich 1-P. Mehlich 1-P correlated with loosely bound-P (Table 5). Correlation analysis on each depth separately showed that DM and P uptake had slightly better relationships with Mehlich 1-P and with loosely bound-P in the 7.5- to 15-cm depth than for these indices of P availability in 0- to 7.5-cm depth (data not shown). Dry matter and P uptake were positively related to Al-P only in the 7.5- to 15-cm depth (r = 0.80** and 0.79**, respectively). In the 0- to 7.5-cm depth, Al-P was negatively related to Mehlich 1-P and loosely bound-P (r = −0.56** and −0.68**, respectively), but in the 7.5- to 15-cm depth Al-P was positively related to Mehlich 1-P and loosely bound-P (r = 0.95** and 0.57**, respectively).

Dry matter of the second wheat crop was positively related to Mehlich 1-P and loosely bound-P and negatively related to Al-P and Fe-P in the soil prior to growth of the second wheat crop (Table 5). Phosphate uptake by the first wheat crop was positively related to loosely bound-P and negatively related to Fe-P. Dry matter and P uptake in crop II wheat were not related to inorganic P fractions measured after the second wheat crop, but were somewhat related to Mehlich 1-P (r = 0.54* and 0.51*, respectively).

Table 4. Effect of alum sludge incorporation on soil P fractions of the entire soil volume (0- to 15-cm depth) after the second wheat crop.

Sludge rate	LB-P†	Al-P	Fe-P	Ca-P
g kg^{-1} soil	mg P kg^{-1} soil			
0	3.5	111.8	47.6	27.7
4.45	2.4	117.0	45.4	25.5
8.9	1.7	117.3	50.7	21.3
17.8	2.0	121.2	55.8	25.5
ANOVA	**	NS‡	**	NS

** ANOVA significant at the 0.01 probability level.
† Loosely bound-P.
‡ NS = not significant.

DISCUSSION

Surface-applied alum sludge decreased DM and P uptake in the P-fertilized soil. The slight increase in DM and P uptake observed in the zero P treatment indicates that the sludge may have provided some nutritional benefits where P fertility was low. Similar results for tomato [*Lycopersicon lycopersicum* (L.)] grown in Fe-sludge-treated soil were attributed to sludge interaction with highly soluble P from fertilizer, but not native P (Elliott and Singer, 1988). However, such interactive results were not found for Mehlich 1-P (Table 2) and inorganic P fractions (Table 3). The extractable P in the sludge was much lower than that in the soil (Table 1) and probably did not contribute to P nutrition. Instead, sludge decreased wheat response to applied P. This is seen in the decreased effect of added P on DM as sludge rate increased.

The rather limited effect of alum sludge on DM and P uptake of the first wheat crop likely was due to three

Table 5. Correlation coefficients of linear regression between Mehlich 1-P and inorganic P fractions after the first wheat crop (mean of both depths) and P uptake and DM in both wheat crops.

Soil P after crop I wheat	Crop I wheat			Crop II wheat	
	DM	P uptake	Mehlich 1-P	DM	P uptake
Mehlich 1-P	0.88**	0.91**	–	0.60*	0.36NS†
LB-P‡	0.71**	0.84**	0.91**	0.79**	0.67*
Al-P	0.47NS	0.64*	0.39NS	−0.56*	−0.29NS
Fe-P	−0.38NS	−0.64*	−0.64*	−0.80**	−0.74*

*,** Correlation significant at the 0.01 and 0.05 probability levels, respectively.
† NS = not significant.
‡ Loosely bound-P.

factors. Firstly, the low amount of supplied N (40 mg N kg^{-1}) may have limited plant response to available P, especially at the lower sludge rates where P was more available. Analysis of the plant tissue showed that N was deficient (Ward et al., 1973) in the 11 and 22 mg P kg^{-1} P treatments (20.3 and 17.7 g N kg^{-1}, respectively). Secondly, the sludge treatments applied to the first wheat crop were imposed during the growing period and, therefore, the sludge treatments were not effective throughout the 50-d growing period. Thirdly, during the growing period of the first wheat crop, the sludge solids remained within the surface 2.5 cm of the soil and did not affect the entire soil volume.

In contrast, the solid portion of the sludge was incorporated throughout the whole soil volume for the second wheat crop and therefore was in greater contact with previously added P and plant roots. Alum sludge caused a much greater reduction in DM and P uptake in this crop as compared to crop I wheat. It appears that the solid portion of the sludge affected plant P nutrition by decreasing soluble soil P levels. The increased P retention capacity that resulted from application of 4.45 g alum sludge kg^{-1} soil was sufficient to cause almost maximum reduction in the availability of applied P. Consequently, the higher sludge rates had little added effect on DM and P uptake. At the 4.45 g kg^{-1} sludge rate, soil solution P and extractable P levels were insufficient for optimum plant nutrition.

Phosphorus retention was likely associated with the sludge solids, not the liquid portion of the sludge. The indices of P availability (loosely bound-P and Mehlich 1-P) decreased with sludge rate only in the surface 7.5 cm after the first wheat crop and correlated with plant DM and P uptake. Although the liquid portion of the alum sludge equilibrated with the entire soil volume in crop I wheat, it did not affect P availability and inorganic forms of P in the 7.5- to 15-cm depth. However, when the solid portion of the sludge interacted with the entire soil volume, the effect of sludge on loosely bound-P, Al-P, and Fe-P on DM and P uptake of the second wheat crop was similar to that observed in the surface 7.5 cm of the soil of the first wheat crop. Additional studies found the solids to have a tremendous P-fixation capacity (Cox, A.E. 1993. Effect of alum sludge application on phosphate and metal chemistry in an Atlantic Coastal Plain soil. M.S. thesis. Clemson Univ., Clemson, SC).

Applied P was probably held as Al-P, since after both wheat crops it was the only fraction (besides loosely bound-P in crop I wheat) that increased with P rate. Although the effect of P fertilization on Al-P was less in the surface 7.5 cm where the sludge solids accumulated than in the 7.5- to 15-cm depth, the Al-P in the surface was probably less soluble or more strongly retained and resulted in a decrease in loosely bound-P and Mehlich 1-P. This relationship shows that Al-P extracted in the fractionation scheme does not distinguish between available Al-P and unavailable Al-P. Dempsey et al. (1990) have also shown that P retention of WTS significantly decreased extractable P (Bray-1 P). Phosphorus fertilization increased growth and P uptake of the first wheat crop, but there was no residual effects of P application on growth of the second wheat crop. Phosphate applied initially may have been transformed into forms with an inconsistent degree of availability before the end of the growing period of the second wheat crop. Barrow (1980) indicated that over an extended period after P fertilization, P extractability and the use of applied P by plants may be significantly reduced. Since P was applied only before crop I wheat, this crop responded to the increase in labile P that was due to P fertilization. However, only a small portion of the applied P (<15%) was removed by crop I wheat leaving a significant soil pool of residual fertilizer P. During the growing period of crop II wheat, most of this residual P was probably associated with the sludge solids as Al-P, which apparently was relatively unavailable. This is indicated by the increase in Al-P observed after crop II wheat. Following P application, the level of loosely sorbed P in soils may decrease relatively quickly (Hooker et al., 1980) unless replenished by fertilization (Sharpley and Smith, 1985).

Mehlich 1-P and loosely bound-P gave a good estimate of P availability in crop I wheat, and to a lesser extent, in crop II wheat. The loosely bound-P should represent the most readily available form of soil P. Susuki et al. (1963) noted that since only a small amount of P is removed by cropping, loosely bound-P may be the major pool supplying P to plants in greenhouse experiments. The good relationship found between Mehlich 1-P, loosely bound-P and P availability in crop I wheat is due mainly to P uptake by wheat in the lower soil depth (7.5–15 cm) where P was more available and not affected by sludge application. Aluminum-P in the 7.5- to 15-cm depth was probably readily plant-available. This is shown by the high correlation observed for DM, P uptake, and Mehlich 1-P with Al-P in the 7.5- to 15-cm depth of crop I wheat. Al-Abbas and Barber (1964) have also shown that loosely bound-P and Al-P were positively related to P availability. Release of Al forms of P may have a significant role in replenishing solution P and loosely bound-P in soils and, subsequently, may be related to plant P nutrition. Iron-P was probably not exploited by either wheat crop. This is indicated by its negative relationship with DM and P uptake.

The possibility that the low pH of the soil used in this study can contribute to the decrease in plant growth associated with alum sludge application needs to be considered. Cox (1993. Effect of alum sludge application on phosphate and metal chemistry in an Atlantic Coastal Plain soil. M.S. thesis. Clemson Univ., Clemson, SC) showed that the applied sludge did not increase availability of some metals studied (aluminum, cadmium, copper, lead, and zinc). However, sludge application increased manganese (Mn) levels in wheat tissue in both crop I wheat (from 300 mg Mn kg^{-1} at zero sludge to 400 mg Mn kg^{-1} at 17.8 mg kg^{-1} sludge) and crop II wheat (from 600 mg Mn kg^{-1} at zero sludge to 900 mg Mn kg^{-1} at 17.8 mg kg^{-1} sludge). However, Lucas et al. (1994) have shown that the effect of Mn accumulation (800 mg Mn kg^{-1}) on DM yield of fescue grown in an alum sludge-amended (40 mg kg^{-1} dried sludge) acid Ultisol was minimal compared to the effect of P deficiency. In our study, the role of Mn in limiting DM yield of wheat was probably also relatively minor.

Surface-applied alum sludge had little effect on P availability to wheat. However, incorporation of the sludge into the entire soil volume caused a decrease in P availability. Reduced P availability resulted from a decrease in loosely bound-P due to retention of P on Al compounds in the sludge solids. Of the inorganic P fractions studied, loosely bound-P was the best predictor of P availability in the sludge-amended soil. Mehlich 1-P was also a good indicator of P availability in alum sludge-amended soil. Fertilizer P requirements will be higher on sludge-amended soils than on unamended. Traditional soil testing methods (Mehlich 1-P) can be used to determine fertilizer P needs.

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