Water Treatment Sludge Influence on the Growth of Sorghum-Sudangrass

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ABSTRACT

Disposal of water treatment sludges (freshwater coagulant sludges), which are primarily amorphous Fe and Al compounds, poses a management problem for most municipalities in Colorado and other states. Previous studies indicate that water treatment sludges have a high capacity to fix P and that plant P deficiencies develop when plants are grown in sludge-soil mixtures. No attempt has been made to quantify the ability of water treatment sludges to fix P to determine specific application rate recommendations. This research was initiated to determine acceptable application rates of three types of water treatment sludges added to the Colby (Ustic Torriorthent; pH = 7.5) and Red Feather (Lithic Cryoboralf; pH = 5.5) soils. A greenhouse study was conducted utilizing mixtures of an alum, iron, or organic polymer sludge combined with each of the two soils at rates of 0, 5, 10, 15, 20, and 25 g kg^{-1}. Three cuttings of sorghum-sudangrass [*Sorghum bicolor* L. Moench 'NB280S'-*S. sudanense* (Piper) Stapf] were taken. The Langmuir adsorption isotherm approach gave an accurate prediction of the relative fixation capacity of different sludges and consequently the effect of different sludge rates on P uptake by plants. Total plant yield and plant uptake data indicated that positive plant growth responses to sludge above those in the control (0 g kg^{-1}) were the result of improved Fe availability in the Colby soil, and possibly increased soil pH in the Red Feather soil. Yields declined at higher sludge application rates (15 - 25 g kg^{-1}) as compared to low application rates (5 - 10 g kg^{-1}) probably due to increased P fixation by sludge. Plant concentrations of Al, Cu, Mn, Ni, and Pb were not high enough to decrease plant growth; however, Cd concentrations associated with 20 and 25 g alum sludge kg^{-1} Red Feather soil were greater than 2 mg kg^{-1}. This is the upper limit reported for normal concentrations in plants and it may pose a threat to livestock that consume this forage.

DISPOSAL of water treatment sludge (freshwater coagulant sludge) is creating a problem due to continuous production of sludge and limited disposal area. Sludge is often dewatered in lagoons and then transported to landfill sites. Land application of liquid or dry sludge is a low cost alternative for disposal that is currently being investigated. Chemical properties of water treatment sludges are variable and depend on impurities in the water flowing into the treatment facility. In the water treatment process, a coagulant is added to aid in settling suspended particles. Substances commonly added as a coagulant include $FeCl_3$, $Al_2(SO_4)_3 \cdot 14H_2O$, and organic polymers. Calcium oxide and/or $Ca(OH)_2$ are also commonly used in the water treatment process and may result in alkaline sludge. The resulting waste sludge materials will be referred to as iron sludge, alum sludge, organic polymer sludge, and lime sludge, respectively, although a combination of these reagents is commonly used.

Only a few studies have reported the consequences of land application of water treatment sludges with respect to plant growth and environmental impact. Alum sludge applied at rates of 5% by volume or greater reduced marigold (*Tagetes* sp. cv. Lemondrop)

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growth as measured by oven-dry plant weight (Bugbee and Frink, 1985). As the amount of sludge added was increased, a decrease in plant growth was directly correlated to a decrease in plant tissue total P concentration. There was no affect of alum sludge (17.5 Mg sludge ha^{-1}) on growth of sugar maple (*Acer saccharum* Marsh.) or a coniferous forest of eastern hemlock [*Tsuga canadensis* (L.) Carr.] (Bugbee and Frink, 1985; Grabarek and Krug, 1987). The application of a $FeCl_3$ sludge at the rate of 60 g kg^{-1} was found to produce P deficiencies in tomato (*Lycopersicon esculentum* Mill.) plants (Elliott and Singer, 1988).

Phosphorus fixation includes the precipitation of solid P minerals from solution and adsorption of phosphate on solid surfaces. Adsorption may be defined as a net accumulation of a substance at an interface; precipitation can be defined as an accumulation of a substance to form a new bulk solid phase (Sposito, 1984). The Langmuir equation was developed to model the adsorption of gas on a solid phase. However, it has been illustrated both mathematically and experimentally that the Langmuir equation may be used to model precipitation reactions as well as adsorption (Veith and Sposito, 1977). The advantage of using the Langmuir equation is that it is possible to define an adsorption capacity.

Freshwater coagulant sludges may serve as effective liming agents. Alum sludge applied at a rate of 17.5 Mg ha^{-1} has been shown to increase the pH of a forest soil (pH 5.0) by about 1 unit (Bugbee and Frink, 1985). Che et al. (1988) applied lime sludges having a pH from 9.6 to 11 to a soil with an initial pH of approximately 6.5 and reported that the lime sludges increased soil pH to a greater extent than did agricultural limestone on a $CaCO_3$ equivalent basis.

Addition of alum sludge at rates as low as 0.8 g kg^{-1} soil resulted in improved soil aggregation and increased water retention. An increase in the growth of maize (*Zea mays* L.) was also reported (Rengasamy et al., 1980).

Another potential benefit of water treatment sludges, particularly iron-sludge, may be an increased availability of Fe to plants grown in Fe-deficient soils. Iron minerals that may be expected to form in water treatment sludge where $FeCl_3$ has been added as a coagulant include amorphous $Fe(OH)_3$, $KFe_3(SO_4)_2(OH)_6$ (jarosite), and $Fe_3(OH)_8$ (ferrosic hydroxide). All three of these forms of Fe result in a higher level of plant-available Fe than soil-Fe (Vlek et al., 1974; Lindsay, 1979). The most likely of these solids to form may be amorphous $Fe(OH)_3(s)$.

Previous research indicates that water treatment sludges contain low soluble concentrations of toxic elements, including heavy metals (Grabarek and Krug, 1987). This potential problem merits further investigation due to the considerable chemical variability of sludges. In addition to plant growth response, plant toxicity can be evaluated by measuring total sludge content, plant tissue concentration, and NH_4HCO_3–diethylenetriaminepentaacetic acid (AB-DTPA) soil extractable levels of toxic elements. The AB-DTPA extraction has been used to correlate extractable heavy metals with plant uptake of metals for sewage sludge-amended soils (Barbarick and Workman, 1987).

The goal of this study was to determine acceptable application rates of alum, organic polymer, and iron sludges to both a calcareous agricultural soil and a forest soil from Colorado. The objectives and hypotheses tested in this study were as follows:

1. Examine fixation of plant-available P when sludges are combined with soil. *Hypothesis*: At low sludge application rates (<10 g kg^{-1} soil), P fixation is minimal and causes no decrease in plant growth.
2. Utilize P fixation isotherms to predict the extent of phosphate removal by sludge materials and a subsequent reduction in plant available P. *Hypothesis*: The determination of P fixation capacity of sludges using a Langmuir isotherm approach provides an indication of the relative P fixation capacity of the sludge-soil mixtures.
3. Determine the influence of added sludges on the availability of Fe to plants. *Hypothesis*: Iron sludges contain highly soluble forms of Fe and will increase plant growth if added to an Fe-deficient soil.
4. Investigate the degree of phytotoxicity resulting from sludge application to soils. *Hypothesis*: Addition of water treatment sludges at rates of 25 g kg^{-1} soil or less does not cause plant toxicity.
5. Evaluate sludges from Colorado water treatment plants as liming agents. *Hypothesis*: Alkaline sludge materials effectively raise the pH of acidic soils.

MATERIALS AND METHODS

All sludge samples were air-dried lagoon samples. The alum sludge had aged for about 1 yr, whereas the iron and organic polymer sludge had aged for about 2 yr. Total elemental analysis of the sludges (Table 1) were determined by $HNO_3/HClO_4$ digestion. Total N was determined by the Kjeldahl digestion method. Initial saturated paste pH of the two soils and three sludges was also measured (Table 2). Extractable elements were measured by the AB-DTPA soil test (Barbarick and Workman, 1987; Workman et al., 1988). Nitrogen, K, and P fertilizer were applied based on recommended fertilization rates using data from the AB-DTPA soil test (Table 2). Data used in the construction of P adsorption isotherms were obtained for each of the three sludges and the two soils. Solutions of 0, 2, 5, 10, 15, 20, 40, 60, 80, and 100 mg P L^{-1} were prepared by dissolving appropriate amounts of KH_2PO_4. The final solutions each contained 0.1 mol KCl L^{-1} to maintain a relatively constant ionic strength. Twenty-five milliliters of each solution were added to 0.5 g sludge or soil (<2-mm particle size) in 50-

Table 1. Total elemental content of water treatment sludges.

Element	Units	Alum	Iron	Organic polymer
$CaCO_3$ equiv.	g kg^{-1}	–	170	11
N	g kg^{-1}	7.7	3.1	6.4
Ca	g kg^{-1}	1.2	72	5.8
Mg	g kg^{-1}	1.9	8.6	14
Na	g kg^{-1}	0.2	0.6	0.4
K	g kg^{-1}	2.7	3.2	12
P	g kg^{-1}	1.3	3.6	1.3
Al	g kg^{-1}	77	27	79
Fe	g kg^{-1}	23	110	40
Mn	g kg^{-1}	0.4	13	0.4
Cu	mg kg^{-1}	32	127	191
Zn	mg kg^{-1}	72	419	89
Ni	mg kg^{-1}	9	44	24
Mo	mg kg^{-1}	11	29	7
Cd	mg kg^{-1}	2.8	3.7	0.9
Pb	mg kg^{-1}	149	72	54

mL screw-top centrifuge tubes. The tubes were agitated for 4 h on a reciprocating shaker, then centrifuged at 4000 rpm for 12 min. Phosphorus concentration in the supernatant was measured using a molybdate-blue procedure (Watanabe and Olsen, 1965). At separate times of shaking, three replications of each adsorption measurement were completed. Adsorption data were fitted to the linear form of the Langmuir equation (Eq. [1]) by regression analysis (Steel and Torrie, 1980), and the adsorption capacities (*b*) were calculated.

$$C/(x/m) = 1/Kb + C/b \qquad [1]$$

where C is the equilibrium concentration of the adsorbate, x/m is the weight of adsorbate per unit weight adsorbent, K is a constant related to binding energy, and b is the adsorption maximum.

A greenhouse study included combinations of each of the three sludges mixed with each of the two soils. The soils were air-dried and seived through a 6.6-mm screen. The sludge materials were air-dried and seived to <2-mm particle size. Three replications of each sludge rate (0, 5, 10, 15, 20, 25 g sludge kg^{-1} soil) for each sludge-soil combination were prepared. The air-dry moisture content of each of the three sludges was determined by oven-drying at 105 °C for 24 h. The required oven-dry equivalent mass of sludge was then added to 2.5 kg of soil and mixed for 1 min in an inverting mixer. The mixture was placed in 10-cm diam. by 38 cm long PVC pipe with a plastic plate glued to the bottom to prevent drainage of soil solution.

Sorghum-sudangrass [*Sorghum bicolor* L. Moench 'NB280S'-*S. sudanense* (Piper) Stapf] seeds were planted six per pot and thinned after 2 wk to retain only the two most vigorous plants. Treatments were arranged in a randomized complete block design. Field capacity moisture content [18% for Colby, (Ustic Torriorthent) and 12% for Red Feather (Lithic Cryoboralf) soil] was maintained for each treatment by watering all pots to field capacity (by mass determination) every 2nd or 3rd d until completion of the final plant cutting. Two weeks after planting fertilizer solutions were added to all treatment combinations of both soils. Fifty milliliters of 0.02 mol $Ca(H_2PO_4)_2$ L^{-1} and 50 mL of 0.12 mol NH_4NO_3 L^{-1} were added to all treatment combinations of both soils. Fifty milliliters of 0.051 mol KCl L^{-1} was added to the Red Feather soil only. An additional treatment level was included by adding 100 mL of 0.02 mol $Ca(H_2PO_4)_2$ L^{-1} to a duplicate set of the highest sludge application rates of 25 g kg^{-1} for each sludge-soil treatment combination. After the first plant harvest, fertilizer additions were repeated, except that no P fertilizer was added to the Colby soil. Following the second cutting, the initial fertilizer treatments were repeated.

Table 2. pH and AB-DTPA–extractable concentrations for water treatment sludges and soils.

	Sludges			Soils	
	Alum	Iron	Organic polymer	Colby	Red Feather
pH:	5.1	7.3	6.1	7.5	5.2
	mg kg^{-1}				
Element					
Ca	124	71	225	324	320
Mg	9	385	321	150	31
Na	14	267	35	7	5
K	37	71	393	541	91
P	ND†	ND	0.5	11	2
Al	110	1.1	2.8	2	11
Fe	127	198	92	2	165
Cu	4	27	95	1.1	0.8
Zn	3	59	6	1	2.7
Ni	0.2	1.2	0.8	0.2	0.2
Mo	0.5	1.8	0.1	ND	0.1
Cd	0.8	0.7	0.2	ND	0.1
Pb	13	3	4	0.8	5.7
NO_3-N	1	3	13	1	1

† ND = nondetectable.

Three cuttings of sorghum-sudangrass were made at 49, 78, and 113 d after planting. Prior to each cutting, visual deficiency symptoms of P and Fe were noted. The plants were cut 10 cm above the soil surface, rinsed in distilled water, and placed in paper bags. The plant samples were oven-dried at 70 °C for 24 h and dry plant mass was measured. Total plant tissue analysis was done by HNO_3 digestion (Havlin and Soltanpour, 1980). Total P, Zn, Fe, Al, K, Mn, Cu, Cd, Pb, and Ni were measured by inductively coupled plasma optical emission spectrophotometer (ICP).

Soil samples were taken at the conclusion of the experiment using a 2-cm core sampler to remove soil from the surface to the bottom of each pot. Saturated-paste pH of all soil-sludge treatment combinations were measured after a 12-h equilibration period.

Data for the Red Feather and Colby soils were analyzed separately. For each soil, the treatments were analyzed in two sets. Analyses of variance were done for the first data set, which included sludge application rates of 0, 5, 10, 15, 20, and 25 g kg^{-1}. The sludge × rate interaction, sludge treatment effect, and sludge rate effect was determined. Regression analysis of application rate vs. total plant yield was completed. Least significant difference (LSD) values were calculated at the 0.05 probability level. Separate LSD values for the main effects of sludge type averaged across rates, rate averaged across sludge type, and also the simple effects of application rate for each sludge type were determined. The second data set included the treatments containing 25 g kg^{-1} rate and the 25 g kg^{-1} rate with additional P fertilizer (referred to as added P). A mean separation of dry matter yields using LSD was completed for the second data set (Steel and Torrie, 1980).

RESULTS AND DISCUSSION

The alum and iron water treatment sludges exhibited a significantly larger P adsorption capacity (*b*) than the organic polymer or the two soils (Table 3). The alum and iron sludge adsorbed from 10 to 37 times more P than the two soils.

Colby Soil

Significant sludge rate, sludge type, and rate × type interaction effects were found for dry matter production of sorghum-sudangrass from the Colby soil (Heil, 1988). Addition of only 5 g kg^{-1} of any sludge produced significantly greater dry matter production than the control treatment (0 g kg^{-1}) (Fig. 1). Overall, the largest production was found with the 20 g iron sludge kg^{-1} rate. Plant growth responses to sludge rate in the Colby soil were modeled with quadratic equations for the alum (Eq. [2] and iron (Eq. [3]) sludges and a linear equation for the organic polymer (Eq. [4])

Table 3. Adsorption capacities (*b*) and coefficients of determination from Langmuir isotherms for water treatment sludges and soils.

Sludge	*b*, μg kg^{-1}	R^2
Alum	3570b*	0.986**
Iron	4700b	0.994**
Organic polymer	737a	0.986**
Soil		
Colby	352a	0.990**
Red Feather	128a	0.995**

* Numbers followed by the same letter are not significantly different at the 0.05 probability level according to the LSD.

** Significant at the 0.01 probability level.

$$\text{Alum: } Y = 7.2 + 1.23X - 0.041X^2, \quad R^2 = 0.834^{**} \qquad [2]$$

$$\text{Iron: } Y = 7.0 + 1.52X - 0.044X^2, \quad R^2 = 0.942^{**} \qquad [3]$$

$$\text{Organic polymer: } Y = 7.0 + 0.15X, \quad R^2 = 0.792^{**} \qquad [4]$$

where Y is the total plant dry matter in g pot^{-1} and X is the sludge application rate (g kg^{-1}).

For various harvests, Heil (1988) noted Fe deficiency symptoms in plants grown in the controls, the 5 and 10 g kg^{-1} rate of alum and essentially all rates of the organic polymer sludge treatments. The iron sludge and, at higher rates, the alum sludge corrected iron deficiencies in the calcareous Colby soil (see Table 2 for extractable Fe in this soil). Table 4 indicates that increasing the rate of the iron and alum sludges generally increased plant Fe concentrations in the plant material from the first two harvests taken from the Colby soil. In the third cutting, higher plant concentrations of Fe were measured in the control due to 1.4 to 4.3 fold lower plant yields than were found with the 5 g kg^{-1} rate (i.e., a tissue concentration effect). The total Fe uptake was significantly affected by sludge rate, sludge type and the rate × type interaction. Figure 2 illustrates that both the iron and alum sludge rate of 5 g kg^{-1} more than doubled the total Fe uptake compared to the 0 g kg^{-1} rate (controls). The iron and alum sludges increased dry matter production in the Colby soil by increasing plant-available Fe as evidenced by the disappearance of deficiency symptoms and the increase in Fe concentrations and total Fe uptake. Havlin and Soltanpour (1981) observed Fe deficiency symptoms on sorghum grown in the Colby soil (AB-DTPA extractable Fe = 4.3 mg kg^{-1}). They applied Fe-EDDHA [Ferric ethylene diamine di (0-hydroxyphenyl acetate)] to this soil and corrected the deficiency symptoms and increased the dry matter yield.

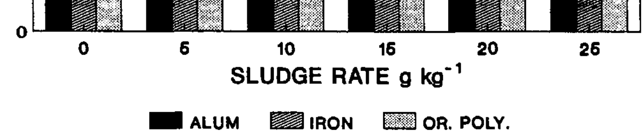

Fig. 1. Total dry matter yield for the Colby soil.

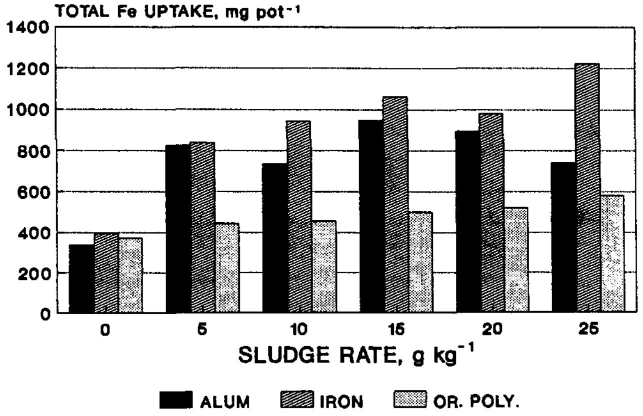

Fig. 2. Total Fe uptake for the Colby soil.

The sludges supplied the following range of total N: alum, 32 to 160 mg N kg^{-1}; iron, 16 to 78 mg N kg^{-1}; organic polymer, 38 to 192 mg N kg^{-1}. A total of 202 mg N kg^{-1} had been added as NH_4NO_3 to all pots. The total amount of N supplied by the sludges was significant; however, only small amounts of NO_3-N (Table 2) were added. Most of the N in the water treatment sludges was in organic form; therefore, most of the N would not have been available during the study. Also, adequate fertilizer N had been added to all treatments. Twice the recommended level of N (Soltanpour et al., 1985) for field applications were added to all pots. The N added with the sludges may have produced some of the yield responses; however, most of the plant response associated with iron sludge was due to the addition of plant-available Fe.

Table 4. Plant tissue Fe concentrations for the Colby soil.

Sludge	Rate	Cutting 1	Cutting 2	Cutting 3
	g kg^{-1}	mg Fe kg^{-1}		
Alum	0	64	35	91
	5	71	40	63
	10	80	44	49
	15	80	51	67
	20	84	55	60
	25	97	55	57
	LSD (0.05)	13	10	29
Iron	0	54	35	109
	5	82	41	67
	10	78	37	58
	15	87	50	63
	20	80	45	48
	25	84	62	77
	LSD (0.05)	13	10	29
Organic polymer	0	63	32	84
	5	66	38	56
	10	67	38	77
	15	75	38	79
	20	71	33	58
	25	73	35	74
	LSD (0.05)	13	10	29
Avg. for sludges	0	61	34	95
	5	74	40	62
	10	75	39	62
	15	81	46	70
	20	78	44	55
	25	85	51	69
	LSD (0.05)	8	6	17
	Average rates			
Organic polymer		69	36	72
Iron		78	45	70
Alum		79	47	65
	LSD (0.05)	5	4	12
	F test			
Sludge		**	**	NS
Rate		**	**	**
Sludge × rate		NS†	*	NS

** Significant at the 0.01 probability level.

† NS = nonsignificant at the 0.05 probability level.

Generally, sludge type and rate plus their interaction significantly affected the P content of the sorghum-sudangrass grown in the Colby soil (Table 5). The application of even the lowest sludge rate produced lower P concentrations. The average P concentrations within each cutting for the alum and iron sludges were not significantly different. This was expected since the P adsorption capacities (*b*) of these sludges were not significantly different (Table 3). Additions of the organic polymer sludge, overall, produced significantly higher plant P concentrations than the other two sludges. These results again correspond to the differences found in the *b* values for these sludges. Heil (1988) noted severe P deficiency symptoms for the first cutting from the Colby soil for the highest rate of iron and alum sludge. Further evidence that the iron and alum sludges restricted P uptake while the organic polymer did not is provided in Table 6. Doubling the P application rate within the highest alum and iron sludge rates (25 g kg^{-1}) produced 29 and 13% greater production, respectively, than the high sludge rate with the recommended P fertilizer rate. In contrast, Bugbee and Frink (1985) found that P deficiencies in the 50 g kg^{-1} alum sludge rate were not overcome by doubling the initial P fertilizer rate.

Even though sludge type, sludge rate, and their interaction significantly affected a number of the plant trace metal metal concentrations associated with the Colby soil (Heil, 1988), the metal concentrations generally were within the normal range reported for forages (Logan and Chaney, 1983; Sommers and Barbarick, 1986). The following ranges in plant concentrations were found: 4.4 to 12.0 mg Cu kg^{-1}, 79 to 217 mg Mn kg^{-1}, 0.6 to 1.6 mg Ni kg^{-1}, <0.8 mg Pb kg^{-1}, 8 to 54 mg Al kg^{-1}, 22 to 57 mg Zn kg^{-1}, and 0.09 to 0.83 mg Cd kg^{-1}.

Table 5. Plant tissue P concentrations for the Colby soil.

Sludge	Rate	Cutting 1	Cutting 2	Cutting 3
	g kg^{-1}	g P kg^{-1}		
Alum	0	3.3	4.7	5.4
	5	2.5	1.8	2.3
	10	2.6	1.5	1.8
	15	2.4	1.4	2.0
	20	2.4	1.3	1.7
	25	2.7	1.5	1.9
	LSD (0.05)	0.5	0.3	0.7
Iron	0	3.4	4.8	5.2
	5	2.8	1.7	3.0
	10	2.5	1.4	2.4
	15	2.8	1.6	2.2
	20	2.5	1.5	1.9
	25	2.7	1.8	2.0
	LSD (0.05)	0.5	0.3	0.7
Organic polymer	0	3.5	4.7	4.8
	5	3.0	4.3	4.8
	10	3.2	4.1	5.8
	15	3.2	3.2	5.2
	20	2.8	2.5	4.4
	25	2.6	2.4	4.4
	LSD (0.05)	0.5	0.3	0.7
Avg. for sludges	0	3.4	4.7	5.2
	5	2.8	2.6	3.4
	10	2.8	2.3	3.3
	15	2.8	2.0	3.2
	20	2.5	1.8	2.7
	25	2.7	1.9	2.8
	LSD (0.05)	0.3	0.2	0.4
	Avg. rates			
Organic polymer		3.0	3.5	4.9
Iron		2.8	2.1	2.8
Alum		2.7	2.0	2.5
	LSD (0.05)	0.2	0.1	0.3
	F test			
Sludge		**	**	**
Rate		**	**	**
Sludge × rate		NS†	**	**

** Significant at the 0.01 probability level.

† NS = nonsignificant at the 0.05 probability level.

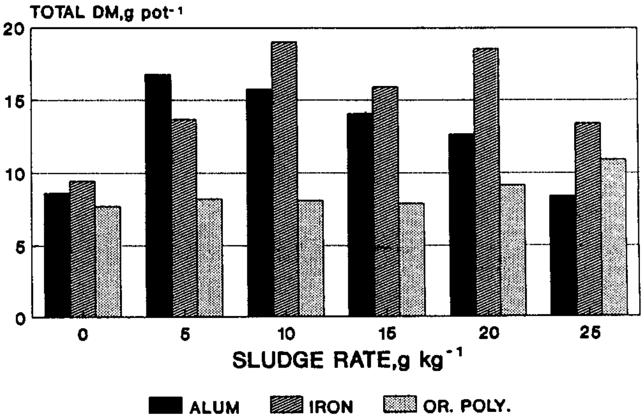

Fig. 3. Total dry matter yield for the Red Feather soil.

Red Feather Soil

Sludge rate, sludge type, and their interaction significantly affected the total dry matter yield of sorghum-sudangrass grown on the acidic Red Feather soil (Heil, 1988). The yield response for each sludge was similar to the Colby soil (Fig. 3). Total Dry matter production was modeled with quadratic responses for the alum (Eq. [5]) and iron (Eq. [6]) sludges and a linear response for the organic polymer sludge (Eq. [7]):

$$\text{Alum: } Y = 10.0 + 1.04X - 0.044X^2, \quad R^2 = 0.816^{**} \qquad [5]$$

$$\text{Iron: } Y = 9.3 + 1.20X - 0.040X^2, \quad R^2 = 0.831^{**} \qquad [6]$$

$$\text{Organic polymer: } Y = 7.3 + 0.105X, \quad R^2 = 0.683^{**} \qquad [7]$$

Table 6. Plant dry matter yield with increased P fertilizer at the highest sludge rate.

Soil	Sludge	Rate	Dry matter
		g kg^{-1}	g pot^{-1}
Colby	Alum	25	12.7
		Added P	16.4
	Iron	25	17.3
		Added P	19.5
	Organic polymer	25	10.6
		Added P	11.4
		LSD (0.05)	2.1
Red Feather	Alum	25	8.4
		Added P	18.7
	Iron	25	13.4
		Added P	22.0
	Organic polymer	25	10.9
		Added P	10.6
		LSD (0.05)	4.3

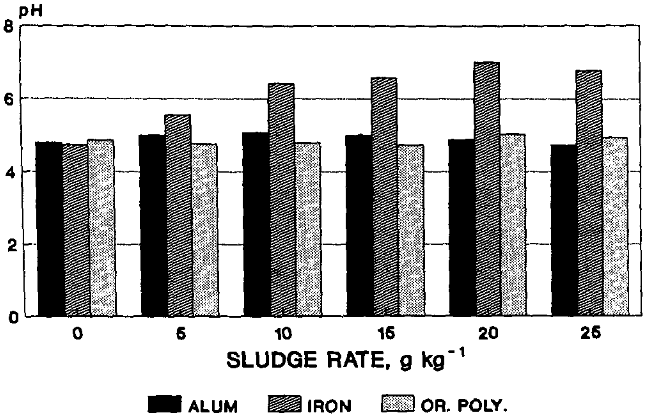

Fig. 4. pH of the Red Feather soil.

where Y is the total plant dry matter in g pot^{-1} and X is the sludge application rate in g kg^{-1}.

The increase in soil pH associated with the addition of iron sludge to the acidic Red Feather soil possibly improved plant growth (Fig. 4). The iron sludge acted as a liming agent (170 g kg^{-1} $CaCO_3$; Table 1) and raised the pH from 4.7 in the control to as high as 7.0 in the 20 g kg^{-1} treatment. The pH of the alum treatments were not changed, yet plant dry matter was increased by the addition of the alum sludge. The significantly higher yields found with the 5 to 20 g alum sludge kg^{-1} may have resulted from improved physical conditions. Rengasamy et al. (1980) reported that addition of as low as 0.8 g alum sludge kg^{-1} to soils decreased the modulus of rupture. Also, the 5 g kg^{-1} rate of alum sludge may have released enough N (32 mg total N kg^{-1}) to produce some of the yield response. Most of the N, however, was probably unavailable (organic N) and all treatments received adequate N so that large yield responses to sludge N were not expected.

As with the Colby soil, the sludge type and application rate and their interaction significantly affected plant P concentrations (Table 7). The trends in P concentration again reflect the greater adsorption capacity of the alum and iron compared to the organic polymer sludge (Table 3). Also, addition of extra P fertilizer to the 25 g sludge kg^{-1} rate produced 123 and 64% increases in dry matter yield for the alum and iron sludges, respectively (Table 6), indicating that the highest alum and iron sludge rates created a deficiency of P.

Trace metal content in the plants grown in the Red Feather soil were affected by sludge type, sludge rate,

Table 7. Plant tissue P concentrations for the Red Feather soil.

		Cutting		
Sludge	Rate	1	2	3
	g kg^{-1}	g P kg^{-1}		
Alum	0	2.3	3.3	4.4
	5	1.2	1.9	3.0
	10	1.3	1.9	1.4
	15	1.0	1.9	1.4
	20	1.0	1.7	1.3
	25	0.9	1.6	1.1
	LSD (0.05)	0.4	0.7	0.9
Iron	0	1.9	3.7	4.5
	5	1.1	1.8	2.5
	10	1.2	2.1	2.1
	15	1.1	2.0	2.1
	20	1.1	1.9	2.0
	25	1.3	1.8	2.2
	LSD (0.05)	0.4	0.7	0.9
Organic polymer	0	1.9	4.4	5.3
	5	1.7	3.6	4.7
	10	1.7	3.3	4.5
	15	1.5	3.3	5.3
	20	1.4	2.9	5.1
	25	1.2	2.6	4.7
	LSD (0.05)	0.4	0.7	0.9
Avg. for sludges	0	2.0	3.8	4.7
	5	1.3	2.4	3.4
	10	1.4	2.4	2.6
	15	1.3	2.4	2.9
	20	1.2	2.2	2.8
	25	1.2	2.0	2.6
	LSD (0.05)	0.2	0.4	0.5
	Avg. rates			
Organic polymer		1.6	3.3	4.9
Iron		1.3	2.2	2.6
Alum		1.3	2.0	2.1
	LSD (0.05)	0.1	0.3	0.4
	F test			
Sludge		**	**	**
Rate		**	**	**
Sludge × rate		**	NS†	**

** Significant at the 0.01 probability level.
† NS = nonsignificant at the 0.05 probability level.

Table 8. Plant tissue P concentrations for the Red Feather soil.

		Cutting		
Sludge	Rate	1	2	3
	g kg^{-1}	mg Cd kg^{-1}		
Alum	0	2.3	3.3	4.4
	5	1.2	1.9	3.0
	10	1.3	1.9	1.4
	15	1.0	1.9	1.4
	20	1.0	1.7	1.3
	25	0.9	1.6	1.1
	LSD (0.05)	0.4	0.7	0.9
Iron	0	1.9	3.7	4.5
	5	1.1	1.8	2.5
	10	1.2	2.1	2.1
	15	1.1	2.0	2.1
	20	1.1	1.9	2.0
	25	1.3	1.8	2.2
	LSD (0.05)	0.4	0.7	0.9
Organic polymer	0	1.9	4.4	5.3
	5	1.7	3.6	4.7
	10	1.7	3.3	4.5
	15	1.5	3.3	5.3
	20	1.4	2.9	5.1
	25	1.2	2.6	4.7
	LSD (0.05)	0.4	0.7	0.9
Avg. for sludges	0	2.0	3.8	4.7
	5	1.3	2.4	3.4
	10	1.4	2.4	2.6
	15	1.3	2.4	2.9
	20	1.2	2.2	2.8
	25	1.2	2.0	2.6
	LSD (0.05)	0.2	0.4	0.5
	Avg. rates			
Organic polymer		1.6	3.3	4.9
Iron		1.3	2.2	2.6
Alum		1.3	2.0	2.1
	LSD (0.05)	0.1	0.3	0.4
	F test			
Sludge		**	**	**
Rate		**	**	**
Sludge × rate		**	NS†	**

** Significant at the 0.01 probability level.
† NS = nonsignificant at the 0.05 probability level.

and their interaction (Heil, 1988). Most of the metal concentrations were within the normal range of concentrations in forages provided by Logan and Chaney (1983) and Sommers and Barbarick (1986). The following ranges in plant metal concentration were found: 3.0 to 11.4 mg Cu kg^{-1}, 80 to 503 mg Mn kg^{-1}, 0.4 to 1.6 mg Ni kg^{-1}, <0.8 mg Pb kg^{-1}, 17 to 44 mg Al kg^{-1}, and 27 to 126 mg Zn kg^{-1}. As shown in Table 8, Cd concentrations were generally >0.5 mg kg^{-1}. This Cd level may pose a threat to livestock consuming this forage (NRC, 1980). The plant concentrations of Cd associated with the 5 g kg^{-1} rate of all three sludges, however, were not significantly different from the control. Higher concentrations of Cd were found in the 15 to 25 g kg^{-1} alum sludge treatments due to the reduced yields (e.g., tissue concentration effect). The alum-treated Red Feather soils were all less than pH 5.1, which contributed to the higher plant Cd concentrations in this set of treatments.

CONCLUSIONS

Low application rates (5 and 10 g kg^{-1}) of both the alum and iron sludges produced greater plant yields associated with both soils without creating a deficiency of P (Objective 1). Apparently, P fixation was minimal at these rates. The Langmuir adsorption capacity, b (Eq. [1]), provided an accurate indication of P fixation by the sludge-soil mixtures (Objective 2). Low application rates (5 - 10 g kg^{-1} or 11 - 22 Mg ha^{-1}) of the iron sludge and higher rates (15 - 25 g ha^{-1}) of the alum sludge corrected Fe deficiencies in sorghum-sudangrass grown in the calcareous Colby soil without producing P deficiencies (Objective 3). The Fe in these sludges was more available than the minerals in the Colby soil. Most trace metal concentrations in the treatments of both soils were within normal ranges (Objective 4). The exception was the Cd concentrations found in the higher rates (20 and 25 g kg^{-1}) of the alum sludge treatments of the Red Feather soil. The iron sludge acted as a liming agent (170 g kg^{-1} $CaCO_3$ equivalent) in the acidic Red Feather soil (Objective 5).

The application of 5 to 10 g sludge kg^{-1} soil or 11 to 22 Mg sludge ha^{-1} of the sludges used in this study could be safely applied to the Colby soil and provide a beneficial plant nutrition effect. If acidic water treatment sludges are applied to acidic soils (e.g., the Red Feather soil) at rates greater than 11 Mg ha^{-1}, it is recommended that the soil should be limed to at least pH 6 to reduce the availability of toxic trace metals such as Cd.

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