Co-Application Effects of Water Treatment Residuals and Biosolids on Two Range Grasses

J. A. Ippolito,* K. A. Barbarick, and E. F. Redente

ABSTRACT

Alum [$Al_2(SO_4)_3$ $14H_2O$] is commonly used in the municipal water treatment process to destabilize colloids for subsequent flocculation and water clarification. Water treatment residuals (WTR) can be classified as a waste material from these treatment plants. Concerns over land application of WTR are due to its postulated reduction of plant available P and potential plant Al toxicity with increasing WTR rates. Co-application of WTR with biosolids may benefit municipalities with biosolids inherently high in P concentrations and in terms of a cost savings by landfill avoidance. In a greenhouse study, we investigated the efficacy of co-application of WTR and biosolids to the native shortgrass prairie species blue grama (*Bouteloua gracilis* H.B.K. Lag) and western wheatgrass [*Pascopyrum smithii* (Rydb.) A. Love]. Our objectives were to quantify co-application effects on plant P and Al concentrations and uptake, biomass production, and WTR P adsorbing capacity. With blue grama, we observed a positive linear relationship between increasing WTR rate and yield and a negative linear relationship with increasing WTR rate and shoot P and Al concentration ($P < 0.10$). With western wheatgrass, increasing WTR rate produced a negative quadratic effect on shoot Al concentration ($P < 0.10$). Some investigators have observed P deficiency symptoms associated with WTR application; however, we did not. Our adsorption study indicated that co-mixing of the City of Fort Collins, CO, WTR and biosolids at ratios of 8:1 will adsorb all soluble biosolids P. Beyond this ratio the WTR could adsorb all biosolids available P and possibly some soil-borne P.

ALUM SLUDGE, also known as water treatment residuals (WTR), may be considered a waste material from municipal drinking water treatment plants. Alum [$Al_2(SO_4)_3$ $14H_2O$] is used in the treatment process to destabilize colloids for subsequent flocculation and water clarification. Biosolids (sewage sludge) is a by-product of wastewater treatment.

In the past, the potential benefits of applying WTR to the soil have been limited. Cornwell and Westerhoff (1981) state "attempts to use coagulation sludges as soil conditioners or stabilizers have had little success." Rengasamy et al. (1980), Dempsey et al. (1989), and Lin (1988) have reported total Kjeldahl N concentrations between 0.5 and 1%. The N may be plant available depending on the WTR mineralization rate.

The total organic C content of WTR is variable. A range of 0.85 to 6.5%, with typical WTR containing 3% total organic C content have been reported (Elliott and Dempsey, 1991; Elliott et al., 1990). Characteristic WTR organic C is stable and resistant to degradation, which is similar to soil organic C (Elliott et al., 1990).

Changes in soil moisture and structure properties have been documented after WTR application. Bugbee and Frink (1985) observed soil moisture retention and aeration improvements from WTR additions, and Rengasamy et al. (1980) observed increased soil aggregation accompanied by an increase in soil water holding capacity with WTR addition. Scambilis (1977) found that both alum and softening sludges modestly increased soil drainage ability and cohesion. El-Swaify and Emerson (1975) showed that precipitation of Al and Fe hydroxides into dispersed clay suspensions, followed by drying, increased the net bonding between clay particles.

Land application of WTR may offer disadvantages due to the potential adsorption of plant available soil P by hydrous oxides of aluminum. Rengasamy et al. (1980) found that application of WTR at 45 Mg ha^{-1} reduced P uptake and yields in maize (*Zea mays* L.). Tissue analysis showed tomato shoots (*Lycopersicon esculentum* L.) (Elliott and Singer, 1988) and lettuce (*Lactuca sativa* L.) (Bugbee and Frink, 1985) grown in potting media amended with WTR had significantly lower P levels.

In a greenhouse study, Heil and Barbarick (1989) applied 0 to 25 g WTR kg^{-1} soil, with additions of 50 mL of 0.02 mol $Ca(H_2PO_4)_2$ per pot, to two soils growing sorghum–sudangrass [*Sorghum bicolor* (L.) Moench–*Sorghum* × *drummondii* (Steudel) Millsp. & Chase]. They observed P deficiencies at the highest WTR application. By doubling the P fertilizer added to the highest WTR application, sorghum–sudangrass yield increased 29 and 123% for both soils, further indicating an adsorption effect by the WTR. Lucas et al. (1994) grew fescue (*Festuca arundinaceae* Schreb.) in lime and WTR amended soil (0–4% WTR by weight) with two different P treatments (50 and 100 mg P kg^{-1} soil) in a greenhouse experiment. They observed linear decreases in yields for both P treatments; however, the higher P application resulted in higher yields over all WTR rates. Other results showed decreased P plant concentrations with increased WTR applications, indicating a P deficiency.

Peters and Basta (1996) planted Triumph 64 wheat (*Triticum* sp.) in alum-treated soils as a qualitative indicator and observed no nutrient deficiencies. Their soils,

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Abbreviations: AB-DTPA, ammonium-bicarbonate diethylenetriaminepentaacetic acid; DM, dry matter; ICP-AES, inductively coupled plasma-atomic emission spectroscopy; WTR, water treatment residuals.

however, had available P levels well above the P requirement for wheat production. In a large scale field study, Geertsema et al. (1994) applied WTR at rates equal to 0, 36, and 52 dry Mg ha^{-1} to loblolly pine (*Pinus rigida* Mill.). They found no significant differences in bioavailable and total P concentrations 30 mo after WTR application and concluded that soil and ground water characteristics and pine growth were not different between amended and unamended plots.

Other alternative methods of WTR use have been examined. Recent investigation into the use of WTR as a poultry litter amendment have been reported. Moore et al. (1995) showed addition of WTR to poultry litter decreased NH_3 volatilization, which is an advantage because volatilization of NH_3 within poultry houses can be detrimental to humans and birds. Decreases in volatilization resulted in higher total N concentrations in poultry litter, making this material a higher quality fertilizer. In addition, WTR application to poultry litter resulted in significantly lower dissolved reactive P concentrations.

Since P is considered to be the primary element of concern with respect to eutrophication of freshwater systems (Schindler, 1977), municipalities may apply WTR beneficially to soil or poultry litter to adsorb P, and subsequently reduce P waterway entry. Peters and Basta (1996) concluded that the addition of WTR reduced excessive amounts of bioavailable soil P, and by increasing the application rate one could continue to decrease the amount of bioavailable P. They further stated that potential adverse environmental impacts from salinity, pH, Al, and total and extractable metals on application of these municipal and industrial amendments should be insignificant. Shreve et al. (1995) examined the effects of adding WTR to poultry litter on P concentrations and load in runoff and evaluated the effects of amended litter on fescue production. They observed decreased P runoff loss and increased forage yields with WTR-amended compared with nonamended poultry litter. Their results indicated WTR amended litter can be a poultry manure management tool for limiting P inputs into surface waters, while increasing forage yields and fertilizer value of litter, and for economically benefitting poultry producers.

In terms of waterway eutrophication, Al salts have documented use in lake rehabilitation. The Wisconsin Department of Natural Resources (1973), in conjunction with the University of Wisconsin, distributed 12.6 Mg of slurried alum in the top 60 cm of water in Horseshoe Lake, Wisconsin. Their intent was to limit plant available P and propagation of algal blooms. Their results showed a decrease in total lake P during the following summer, no large increase in total P in the hypolimnion during the following two summers, a slight increase in water transparency, and a decrease in color. Most importantly, they observed the absence of algal blooms with subsequent improvement in dissolved oxygen conditions. Narf (1985) showed that alum injection in Bullhead Lake, Wisconsin, reduced the average epilimnetic summer total and soluble reactive P by 38 and 92%, respectively. This reduction in P shifted the N/P ratio against the formation of the blue-green algae community. In its place the diatoms, green algae, flagellates, and rotifers flourished and provided a food chain base.

Land co-application of biosolids and WTR is a new concept, but co-disposal is not. Several large cities within the USA practice successful co-disposal of WTR by direct discharge of WTR to sanitary sewer systems (Cornwell and Westerhoff, 1981). This practice results in increased solids loading at the waste water treatment facility with few operating difficulties, and this process is cost-effective for the participating municipality. Co-disposal, however, is only viable if both water and wastewater treatment facilities are in close proximity to one another, and if the WTR does not adversely affect performance or contaminate the waste-water treatment plant.

The USA produces an estimated 0.35 million dry Mg of WTR per year. Current environmental concerns over WTR discharge to receiving waters has resulted in this practice being discouraged in many locales (Lucas et al., 1994). Most WTR currently generated is discharged to sanitary sewers, lagooned, or dewatered and disposed of in landfills (Elliott et al., 1990). Although no federal guidelines exist for WTR, USEPA regions or individual states can prohibit direct discharge (AWWA, 1987). These issues suggest land application of WTR may be a major method of disposal in the future. Of the states that land apply WTR, many currently use USEPA 40 CFR 503 biosolids regulations as a guideline for WTR land application, although these regulations specifically exclude WTR (Carr et al., 1996).

The Colorado Department of Public Health and Environment (1994, 1996) established guidelines regarding the land co-application of WTR and biosolids based on applicable requirements of the Colorado Biosolids Regulations, 4.9.0. They are, however, concerned with the potential reduction of plant available P due to WTR P adsorption, potential Al toxicity to plants from WTR, and additional source of trace metals added to soil from WTR application.

While application of wastewater biosolids have been extensively studied, application of WTR, either alone or in conjunction with biosolids, has been less thoroughly studied. The disposal of WTR alone would be beneficial to soils high in P, since the WTR can adsorb soluble P. Likewise, the co-application of WTR and biosolids may be advantageous to municipalities as a means of disposal of high P bearing biosolids in an environmentally sound manner. Because of WTR's ability to adsorb P, Bugbee and Frink (1985) state that WTR could play a role in the removal of P in sewage treatment plant effluent.

Harris-Pierce et al. (1993, 1994) studied the effects of WTR and biosolids co-application on above-ground plant biomass of four dominant shortgrass prairie species. No significant trends in the total biomass or plant trace element tissue concentrations of the four species [blue grama, western wheatgrass, buffalograss [*Buchloe dactyloides* (Nutt.) Engelm], and fringed sage (*Artemisia frigida* Willd.)] were observed in plots treated with WTR at rates of 5.6 to 22.4 Mg ha^{-1}, when combined with 11.2 Mg ha^{-1} of biosolids.

Our study objectives were to (i) quantify the effects of co-application of the City of Fort Collins, CO, WTR and biosolids on biomass production of blue grama and western wheatgrass in a greenhouse study; (ii) determine co-application effects on P and Al plant concentrations and uptake, and livestock plant consumption limits (P was targeted because of the Al hydroxide P-fixing properties and Al because of potential plant toxicity); and (iii) calculate the WTR P adsorbing capacity.

The hypotheses tested in this study were: increasing the ratio of WTR to biosolids in a mixed material will (i) decrease plant biomass production, (ii) increase shoot Al concentration and Al uptake, and (iii) decrease shoot P concentration and P uptake, where shoot uptake is a function of concentration multiplied by dry matter yield.

MATERIALS AND METHODS

An Altvan sandy loam (fine-loamy over sandy or sandy-skeletal, mixed, mesic Aridic Argiustoll), was air dried and crushed using a rolling pin. Water treatment residuals and biosolids were obtained from Fort Collins water and wastewater treatment facilities and then air dried, crushed, and passed through a 2-mm sieve.

We determined total elemental composition of soil, WTR, and biosolids by a modified $HClO_4$-HNO_3-HF-HCl digestion (Table 1) (Soltanpour et al., 1982) and analyzed the digestate using inductively coupled plasma-atomic emission spectroscopy (ICP-AES). Biosolids total N was measured following a concentrated H_2SO_4 digestion (Bremner and Mulvaney, 1982), and NH_4–N and NO_3–N following a 2 *M* KCl extraction (Keeney and Nelson, 1982). Electrical conductivity and pH were determined using a saturated paste extract (Rhoades, 1982b), organic matter using a modified Walkley-Black method (Nelson and Sommers, 1982), and cation- exchange capacity was determined by the Rhoades method (1982a).

Table 1. Selected chemical characteristics of soil, water treatment residuals (WTR), and biosolids.

Element	Units	Altvan soil	WTR	Biosolids
Ca	g kg^{-1}	2.6	5.7	30.6
Mg	g kg^{-1}	3.8	4.5	5.2
Na	g kg^{-1}	0.06	0.21	0.63
K	g kg^{-1}	4.7	3.8	2.7
P	g kg^{-1}	0.4	0.7	22.2
Al	g kg^{-1}	16.3	74.7	9.9
Fe	g kg^{-1}	13.5	17.8	5.2
Mn	g kg^{-1}	0.28	0.82	0.10
Ti	g kg^{-1}	0.73	0.79	0.10
N	g kg^{-1}	ND†	ND	55.9
NH_4–N	g kg^{-1}	ND	ND	24.7
NO_3–N	mg kg^{-1}	1.0	44.0	9.2
Cu	mg kg^{-1}	6.1	47.6	578.0
Zn	mg kg^{-1}	34.6	53.3	737.0
Ni	mg kg^{-1}	6.6	10.9	22.7
Mo	mg kg^{-1}	<0.1	<0.1	16.3
Cd	mg kg^{-1}	0.3	<0.1	4.7
Cr	mg kg^{-1}	9.3	19.1	49.0
Sr	mg kg^{-1}	22.2	31.1	315.0
B	mg kg^{-1}	46.8	91.6	34.6
Ba	mg kg^{-1}	127.0	95.2	369.0
Pb	mg kg^{-1}	7.9	<2.5	57.0
Si	mg kg^{-1}	464	322	125
V	mg kg^{-1}	35.6	34.3	14.9
pH		6.9	6.9	7.7
EC	dS m^{-1}	0.2	0.7	11.2
O.M.	g kg^{-1}	1.7	6.3	ND
CEC	cmol (+) kg^{-1}	11.8	39.3	ND

† Not determined.

Blue Grama Greenhouse Study

Ten blue grama seeds were germinated on 28 February 1994 in 20-cm diam. by 20-cm tall pots containing 2.5 kg of soil with various co-application rates. Co-application rates were a combination of a constant biosolids application of 5 dry g kg^{-1} soil (an agronomic rate), and varying WTR rates of 0, 10, 25, 50, 100, 150, 200, and 250 dry g kg^{-1} soil. Application rates of WTR and biosolids were based on dry weights. All applications were manually mixed into the surface 2.5 to 5.0 cm of soil. The experiment was arranged as a randomized complete block design with four replications. The soil surface was kept moist by periodic misting with distilled water.

After plant establishment (approximately 8 wk after initial planting), each pot was irrigated to field capacity (26% moisture by weight) two to three times per week and each pot was thinned to three plants per pot. We returned thinned plants back into the pots so as to not remove any nutrients or trace elements. To promote vegetative growth, we cut seed heads off plants and placed them back into each pot.

We harvested plants at a height of 2.5 cm above the soil surface on 14 June 1994. We then rinsed plants with distilled water, dried them at 70°C for at least 48 h, and weighed to determine dry matter yields (DM). Plants were ground to pass through a 20-mesh sieve. We digested a subsample in concentrated HNO_3 (Havlin and Soltanpour, 1980), and analyzed the digestate for P and Al using ICP-AES. Phosphorus and Al plant uptake were determined by taking the DM multiplied by the plant elemental concentration. Data were analyzed using regression analysis and analyses of variance and tested at $P = 0.10$ (Steel and Torrie, 1980).

Western Wheatgrass Greenhouse Study

The experimental approach and statistical analyses were identical to that of blue grama. We germinated plants on 21 July 1994 and harvested on 12 Dec. 1994. In addition, we separated roots from soil to observe possible root aluminum phosphate precipitation. Roots were rinsed in a 0.03% sodium dodecyl sulfate solution, rinsed with distilled water, and oven dried at 70°C for 72 h. We analyzed roots for P and Al in a concentrated HNO_3 digest using ICP-AES.

Water Treatment Residuals Phosphorus Adsorption Study

In an effort to determine a safe co-mixing ratio of WTR and biosolids with regards to P adsorption, we determined the P adsorptive capacity of WTR in a batch study experiment.

Distilled-deionized H_2O (40 mL):biosolids (0.5 g) solutions (80 fold dilution factor) were shaken for 24 h to determine the maximum P released from biosolids in the shortest time span. It was determined that 16 h were required to obtain maximum P release; for the remainder of the tests we chose a 24 h shaking period for convenience.

Then, triplicates of various distilled-deionized H_2O/biosolids dilutions (dilution factor of 20 to 320; various amounts of water/0.5 g biosolids) were shaken to determine to lowest dilution factor of distilled-deionized H_2O/biosolids with the maximum amount of P released (200 fold dilution factor; maximum released ≈ 6900 mg P L^{-1}).

Finally, various amounts of WTR (0 to 8.0 g dry WTR) were added to a known amount of biosolids (0.2 g dry biosolids) to obtain dry weight ratios of WTR:biosolids of 0, 1, 2, 4, 8, 12, 16, 20, 24, 28, 32, 36, and 40. We added 40 mL of distilled-deionized H_2O to all mixtures to create a 200-fold biosolids P dilution and triplicated all treatments. Previous work indicated P adsorbed by WTR was not released into solution at our given WTR rates and 200-fold dilution. All mixtures were shaken for 24 h to ensure that the maximum soluble biosolids P was released. The mixtures were then centrifuged, and the decantate was filtered through Whatman number 42 filter paper and analyzed for P using ICP-AES. We plotted the observed data using an exponential rise equation:

$$Q = a[1 - e^{(-b^{*}x)}] \quad [1]$$

where

Q = WTR adsorbed P, expressed as a % of the maximum biosolids released P;

a = Maximum P adsorbed by WTR as compared with 100% of the biosolids released P, and expressed as a % of the maximum biosolids released P;

b = Constant for change in WTR adsorbed P for a given change in WTR/biosolids ratio; and

x = WTR/biosolids ratio.

RESULTS AND DISCUSSION

Blue Grama Greenhouse Study

Increasing WTR rate, co-applied with a constant biosolids rate, significantly ($P < 0.10$) increased DM yield, and decreased P and Al shoot concentrations (Table 2). The r^2 values, however, of regression equations for all significant effects were <0.50. Phosphorus deficiency or Al toxicity symptoms were not observed with increasing WTR rates.

Heil and Barbarick (1989) also observed an increase in DM and a decrease in plant P concentration with WTR application. They stated that the high adsorptive capacity of WTR, however, can limit P availability even if a secondary source of P (i.e., biosolids) is co-applied. Bugbee and Frink (1985) noted an increase in lettuce yield with a mixture of 33% perlite, 33% peat, and 33% WTR as a potting media as compared to other mixtures of the above three constituents and soil. They explained improvements in growth possibly due to increased aeration and water holding capacity, which overcame the adverse effects of P deficiency. Similarly, Cornell et al. (1995) observed an increase in canopy cover on native rangeland vegetation as compared with lower co-application ratios 3 yr after co-application of 5 dry tons biosolids acre^{-1} with 10 dry tons WTR acre^{-1}. Our DM results are similar; the biosolids may have acted as a bioavailable P source, overcoming the WTR's P adsorptive capacity, while the WTR increased aeration and water holding capacity.

McLaughlin et al. (1981) showed a 1-mo aged amorphous Al gel sorbed approximately 35 times more P than a crystalline gibbsite. They hypothesized P surface adsorption of short-range order hydrous oxides in soils will behave similarly to that of aged Al gels. When applied to soils, the WTR may act similarly to these short-range order hydrous oxides, resulting in decreases in plant shoot Al and P concentrations.

From the nearly neutral soil and waste mixture pH (Table 1) it could be hypothesized that plant Al concentrations would decrease due to possible crystalline $Al(OH)_3$ formation. However, due to soil versus WTR ammonium-bicarbonate diethylenetriaminepentaacetic acid (AB-DTPA) extractable Al (0.65 and 8.17 mg Al kg^{-1} material, respectively) and WTR's chemical composition (amorphous aluminum hydroxide as determined by x-ray diffraction analyses; similar to x-ray diffraction studies by Rengasamy et al., 1980) we anticipated a plant Al content increase with increasing WTR rate.

The AB-DTPA extraction is a qualitative indicator of certain plant available metals found in sludge-amended soils (Barbarick and Workman, 1987; Barbarick et al., 1997). Amorphous aluminum hydroxide has a solubility approximately an order of magnitude greater than gibbsite (Lindsay, 1979), which could lead to slightly higher plant available soil Al concentrations immediately after WTR application. More importantly, soil addition of amorphous Al materials (e.g., WTR) at neutral pH may lead to polynuclear hydroxyl Al species formation. These species are intermediates in the precipitation of solid $Al(OH)_3$, and may or may not be toxic to plants (Marschner, 1995).

From the above inferences and from our observed decrease in shoot Al and P concentrations, we hypothesize the Al and P was sorbed by roots and not significantly translocated to shoots; this issue will be addressed in our discussion of western wheatgrass.

The maximum tolerable levels of dietary P and Al for domestic animals range from 0.8 to 1.5% and 200 to 1000 mg kg^{-1}, respectively (National Research Council, 1980). Our plant concentrations fell well below these tolerable levels (Table 2).

Western Wheatgrass Greenhouse Study

Increasing WTR rate, co-applied with a constant biosolids rate, significantly ($P < 0.10$) affected plant Al concentration (Table 3); the trend being decreasing plant Al concentration with increasing WTR rate. The r^2 value of the regression equation was 0.62. Again, no P deficiency or Al toxicity symptoms were noted, and the concentrations of both elements were well below those considered harmful to domestic animals.

Root P and Al concentrations were not affected by increasing co-applications of these materials (Table 4). The ratio of root P to Al was approximately 1:1. Although we cannot distinguish which root portion con-

Table 2. Effects of water treatment residuals (WTR) and biosolids co-applications on blue grama dry matter yields and P and Al shoot concentrations and uptake.

WTR	Biosolids	Dry matter yields	Shoot P	P uptake	Shoot Al	Al uptake
g kg^{-1}	g kg^{-1}	g pot^{-1}	mg kg^{-1}	mg pot^{-1}	mg kg^{-1}	µg pot^{-1}
0	5	6.9	2180	14.9	36.1	248
10	5	4.2	2010	8.5	32.0	135
25	5	6.2	1340	8.3	33.0	204
50	5	6.8	1760	11.9	27.7	187
100	5	4.7	1520	7.2	25.4	120
150	5	10.8	1520	16.4	24.4	265
200	5	11.3	1610	18.2	30.8	349
250	5	8.6	1320	11.4	23.6	203
			Prob.	Level	(P)	
Regression f-test						
Linear		0.050	0.091	0.327	0.053	0.301
Quad		0.166	0.217	0.644	0.086	0.616
LSD(0.10)		2.8	350	–	4.8	–

Table 3. Effects of water treatment residuals (WTR) and biosolids co-applications on western wheatgrass dry matter yields and P and Al shoot concentrations and uptake.

WTR	Biosolids	Dry matter yields	Shoot P	P uptake	Shoot Al	Al uptake
g kg^{-1}		g pot^{-1}	mg kg^{-1}	mg pot^{-1}	mg kg^{-1}	µg pot^{-1}
0	5	9.7	2790	27.2	52.2	508
10	5	10.4	1750	18.1	51.8	536
25	5	10.1	1520	15.4	38.8	392
50	5	11.0	1310	14.4	40.7	448
100	5	9.2	1620	14.9	44.7	412
150	5	14.2	1490	21.2	44.0	626
200	5	12.1	1470	17.8	43.0	520
250	5	7.4	1810	13.3	58.4	430
			Prob.	Level	(*P*)	
	Regression *f*-test					
	Linear	0.956	0.440	0.376	0.535	0.836
	Quad	0.278	0.196	0.628	0.087	0.787
	LSD(0.10)	–	–	–	7.0	–

tained these elements, Millard et al. (1990) used x-ray photoelectron spectroscopy and observed a similar ratio for PO_4 to Al on the root surface of two barley strains [*Hordeum vulgare* L. (Dayton and Kearney)] grown at pH 4.5. They hypothesized that Al resistant plants may precipitate $AlPO_4$ at the root surface, acting as a barrier and reducing Al transport into the root. Other researchers (Fageria et al., 1988; Taylor, 1991) have suggested, in addition to precipitation, Al chelation, immobilization in nonsensitive sites of cells, or other metabolic exclusion mechanisms as a means of Al resistance.

Phosphorus shoot and root concentrations were correlated ($r = 0.71$) with relatively equal concentrations found in both plant fractions. This emphasizes the fact that P is easily translocated from roots to shoots, thus negating our proposed hypothesis of root P adsorption with decreased shoot translocation. Shoot Al concentrations, however, were negatively correlated with root concentrations ($r = -0.47$; shoot:root ≈ 1:35). This supports the contention that translocation of Al from roots to shoots is low. This also supports our hypothesis relative to blue grama that Al was sorbed by the roots and not significantly translocated to the shoots.

The effects of Al on plant growth tend to be limited to the roots (as with our study), with subsequent impacts on water and nutrient uptake (Pearson, 1966). Mclean and Gilbert (1927) demonstrated the injurious effects

Table 4. Effects of water treatment residuals (WTR) and biosolids co-applications on western wheatgrass root P and Al concentrations.

WTR	Biosolids	Root P	Root Al
g kg^{-1}		mg kg^{-1}	
0	5	2100	1030
10	5	1450	1390
25	5	1070	1650
50	5	1040	1600
100	5	1370	1750
150	5	1150	1210
200	5	1020	1340
250	5	1490	1240
		Prob. Level	(*P*)
	Regression *f*-test		
	Linear	0.475	0.656
	Quad	0.749	0.442
	LSD(0.10)	–	–

of Al on root growth with restricted Al transport to the shoots of rye [*Secale cereale* L. (Rosen)]. Similar results have been shown by Jan and Pettersson (1989) with the growth of Al-tolerant upland rice [*Oryza sativa* L. (BG35)].

Water Treatment Residual Phosphorus Adsorption Study

Based on our experimental data, the Fort Collins WTR adsorbed 99.7% of the available biosolids P (approximately 6900 mg P L^{-1}) at ratios ≥8 to 1 (Fig. 1). The equation describing the curve is:

$$\text{WTR Adsorbed P (\%)} = 99.7[1 - e^{(-0.6351*\text{ratio})}] \quad [2]$$

where ratio = the ratio of WTR/biosolids.

If applied to a soil, the initial biosolids and soil P, the amount of mixture applied, and the depth of mixture incorporation will determine the amount of soil P adsorbed. It is possible that too much WTR applied to a soil, in conjunction with biosolids, can induce P deficiencies.

Heil and Barbarick (1989) studied the adsorptive capacity of a few WTR. They found WTR could adsorb from 737 to 3570 mg P kg^{-1} WTR. The P adsorptive capacity of WTR is a function of WTR age, pH, particle-size fraction and surface area, and the availability of P.

SUMMARY

We reject our hypotheses that increasing the ratio of WTR to biosolids in a mixed material will decrease plant biomass production, increase shoot Al concentration and uptake, and decrease shoot P uptake; we accept

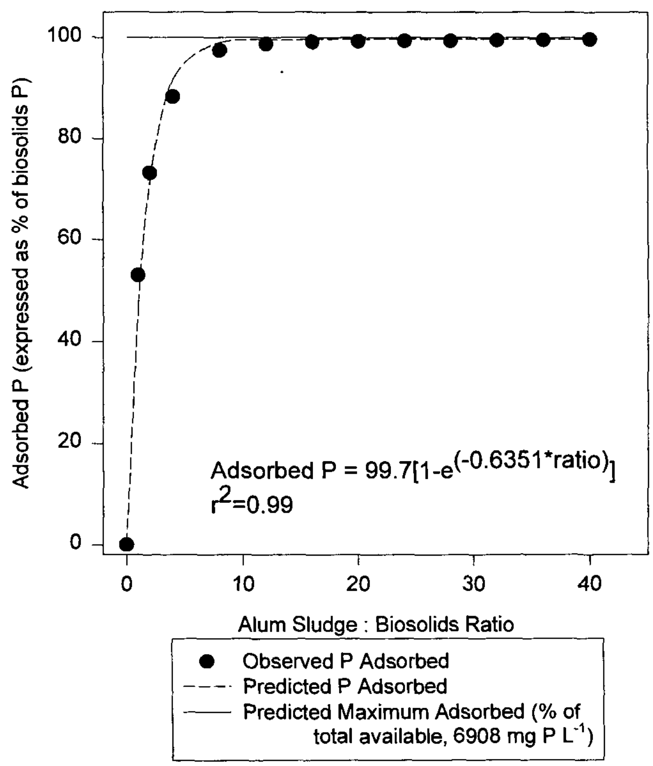

Fig. 1. Water treatment residuals biosolids effect on P adsorption.

our hypothesis that increasing the ratio of WTR to biosolids in a mixed material will decrease shoot P concentration in blue grama. Our blue grama experiment showed that increased WTR rates increased dry matter yields, decreased P and Al shoot concentrations, and had no effect on P or Al shoot uptake. With western wheatgrass, increased WTR rates only affected shoot Al concentration in a decreasing trend. Unlike our findings with blue grama, we did not observe an increase in western wheatgrass dry matter yield. This may be due to the time of year both studies were performed in the greenhouse or differences in plant species. In both studies P deficiency or Al toxicity symptoms were not observed. Plant shoot Al concentrations decreased with increasing WTR rates, and western wheatgrass shoot Al concentrations were negatively correlated with root concentrations. This supports the contention that translocation of Al from roots to shoots is low. This also supports our hypothesis relative to blue grama that Al was sorbed by the roots but not significantly translocated to the shoots.

Data from our adsorption study suggests when comixing and applying WTR and biosolids at ratios of 8:1 or larger, >99% of the immediately soluble biosolids P will be adsorbed. If co-applying WTR and biosolids to soil at ratios greater than 8:1, all biosolids available P, as well as some plant-available soil P, could be adsorbed by the WTR. The amount of plant-available P adsorbed will be determined by the initial biosolids and soil P present, the amount of mixture added to soil, and the depth of mixture incorporation. When co-applying these sludges it is important to observe the 8:1 mixing ratio.

Water treatment residual's innate capacity to adsorb P makes it a useful product for application to high P containing materials or soils that are potential polluters. This would be especially true for soils in locales where waterway eutrophication due to P is a concern. Elliott et al. (1990) summed it up well, stating:

> The application of water treatment sludge to high P soils may be a very good opportunity for farmers and water utilities to reconcile several problems. Many farmers are being pressured to reduce the pollution impact of their traditional fertilization practices. By land applying water treatment sludge to high P containing soils, these traditional practices are less threatened. Additionally, farmers would receive payment for receiving water treatment sludge or have fields plowed during the disposal process. Water utilities could have a more economic and labor conservative disposal method than the more common methods of water treatment sludge disposal, such as landfilling, sewage disposal and coagulant recovery.

As landfill space becomes less available, municipalities must look towards alternative methods of WTR waste disposal. Co-application of WTR and biosolids may benefit municipalities in terms of a cost savings by landfill avoidance and potential reduction of bioavailable P in high P containing biosolids. Land application of WTR alone will also benefit high P containing soils by adsorbing excess P and reducing the risk of nonpoint source pollution losses of P.

If these materials are to be co-applied to land, the co-application should first be based on the agronomic N needs of the crop. Since biosolids contain much higher N levels than WTR, the biosolids application rate should be determined first, then applied. The application of WTR could then take place based on adsorption research and the amount of P an applicator may wish to adsorb. Another alternative would be to co-mix the two agents, determine the N concentration, and then land apply according to the N needs of the crop. As with all material applications, soil testing and material analyses must be conducted to ensure optimum crop yields along with environmental protection.

REFERENCES

AWWA Sludge Disposal Committee. Committee Report. Research Need for Alum Sludge Discharge. June 1987. J. AWWA. 79:6:99.

Barbarick, K.A., and S.M. Workman. 1987. Ammonium bicarbonate-DTPA and DTPA extractions of sludge-amended soils. J. Environ. Qual. 16:125–130.

Barbarick, K.A., J.A. Ippolito, and D.G. Westfall. 1997. Sewage biosolids cumulative effects on extractable-soil and grain elemental concentrations. J. Environ. Qual. 26:1696–1702.

Bremner, J.M., and C.S. Mulvaney. 1982. Nitrogen — total. p. 595–624. *In* A.L. Page et al. (ed.) Methods of soil analysis. Part 2. Chemical and biological properties. 2nd ed. ASA and SSSA, Madison,WI.

Bugbee, G.J., and C.R. Frink. 1985. Alum sludge as a soil amendment: Effects on soil properties an plant growth. Connecticut Agric. Exp. Stn. Bull. 823. Connecticut Agric. Exp. Stn., New Haven.

Carr, S., J.E. Smith, Jr., S.I. McMillan, N.E. McTigue, A. Rubin, and R. Southworth. 1996. Regulatory issues concerning management of water treatment plant residuals. p. 6–16. *In* Technology transfer handbook: Management of water treatment plant residuals. Am. Soc. of Civil Eng. and Am. Water Works Assoc., New York.

Colorado Department of Public Health and Environment. 1996. Revised biosolids regulation 4.9.0. Colorado Dep. of Public Health and Environ., Denver.

Colorado Department Public Health and Environment. 1994. Beneficial use of water treatment sludge and fees applicable to the beneficial use of sludges. 5 CCR 1003-7. Colorado Dep. of Public Health and Environ., Denver.

Cornell, E.S., E.F. Redente, and K.A. Barbarick. 1995. The effect of sewage sludge application on native rangeland vegetation. Annual Rep. Meadow Springs Ranch, Fort Collins, CO.

Cornwell, D.A., and G.P Westerhoff. 1981. Management of water treatment plant sludges. *In* J.A. Borchardt et al. (ed.) Sludge and its ultimate disposal. Ann Arbor Sci. Publ., Ann Arbor, MI.

Dempsey, B.A., J. DeWolfe, D. Hamilton, Y. Lee, R. Liebowitz, and H.A. Elliott. 1989. Land application of water plant sludges. p. 537–543. *In* Proc. 44th Purdue Indus. Waste Conf., West Lafayette, IN. 9–11 May 1989. Purdue Univ., West Lafayette, IN.

Elliott, H.A., and B.A. Dempsey. 1991. Agronomic effects of land application of water treatment sludges. J. AWWA. 83:4:126.

Elliott, H.A., B.A. Dempsey, D.W. Hamilton, and J.R. DeWolfe. 1990. Land application of water treatment sludges: Impact and management. Am. Water Works Assoc. Res. Foundation, Denver, CO.

Elliott, H.A., and L.M. Singer. 1988. Effect of water treatment sludge on growth and elemental composition of tomato shoots. Commun. Soil Sci. Plant Anal. 19:345–354.

El-Swaify, S.A., and W.W. Emerson. 1975. Changes in the physical properties of soil clays due to precipitated aluminum and iron hydroxides: I. Swelling and aggregate stability after drying. Soil Sci. Soc. Am. Proc. 39:1056–1063.

Fageria, N.K., V.C. Baligar, and R.J. Wright. 1988. Aluminum toxicity in crop plants. J. Plant Nutr. 11:303–319.

Geertsema, W.S., W.R. Knocke, J.T. Novak, and D. Dove. 1994. Long-term effects of sludge application to land. J. AWWA. 86:11:64.

Harris-Pierce, R., K.A. Barbarick, and E.F. Redente. 1993. The effect of sewage sludge application on native rangeland soils and vegetation Annual Rep. Meadow Springs Ranch, Fort Collins, CO.

Harris-Pierce, R., K.A. Barbarick, and E.F. Redente. 1994. The effect of sewage sludge application on native rangeland soils and vegetation. Annual Rep. Meadow Springs Ranch, Fort Collins, CO.

Havlin, H.L., and P.N. Soltanpour. 1980. A nitric acid plant tissue digest method for use with inductively coupled plasma spectrometry. Comm. Soil Sci. Plant Anal. 11:969–980.

Heil, D.M., and K.A. Barbarick. 1989. Water treatment sludge influence on the growth of sorghum-sudangrass. J. Environ. Qual. 18: 292–298.

Jan, F., and S. Pettersson. 1989. Varietal diversity of upland rice in sensitivity to aluminum. J. Plant Nutr. 12:973–993.

Keeney, D.R., and D.W. Nelson. 1982. Nitrogen — inorganic forms. p. 648–659. *In* A.L. Page et al. (ed.) Methods of soil analysis. Part 2. Chemical and biological properties. 2nd ed. ASA and SSSA, Madison, WI.

Lin, S. 1988. Effects of alum sludge application on corn and soybeans. *In* Joint Conf. CSCEASCE, Natl. Conf. of Environ. Eng., Vancouver, BC. 13–15 July 1988.

Lindsay, W.L. 1979. Chemical equilibria in soils. John Wiley & Sons, New York.

Lucas, J.B., T.A. Dillaha, R.B. Reneau, J.T. Novak, and W.R. Knocke. Nov. 1994. Alum sludge land application and its effect on plant growth. J. AWWA. 86:11:75.

Marschner, H. 1995. Mineral nutrition of higher plants. 2nd ed. Academic Press, San Diego, CA.

McLaughlin, J.R., J.C. Ryden, and J.K. Syers. 1981. Sorption of inorganic phosphate by iron- and aluminum-containing components. J. Soil Sci. 32:365–377.

McLean, F.T., and B.E. Gilbert. 1927. Aluminum tolerance of crop plants. J. Soil Sci. 24:165–176.

Millard, M.M., C.D. Foy, C.A. Coradetti, and M.D. Reinsel. 1990. X-ray photoelectron spectroscopy surface analysis of aluminum ion stress in barley roots. J. Plant Physiol. 93:578–583.

Moore Jr., P.A., T.C. Daniel, D.R. Edwards, and D.M. Miller. 1995. Effect of chemical amendments on ammonia volatilization from poultry litter. J. Environ. Qual. 24:293–300.

Narf, R.P. 1985. Impact of phosphorus reduction via metalimnetic alum injection in Bullhead Lake, Wisconsin. TB153. Dep. of Nat. Resour., Madison, WI.

National Research Council. 1980. Mineral tolerance of domestic animals. Natl. Academy of Sciences, Washington, DC.

Nelson, D.W., and L.E. Sommers. 1982. Total carbon, organic carbon, and organic matter. p. 570–573. *In* A.L. Page et al. (ed.) Methods of soil analysis. Part 2. Chemical and biological properties. 2nd ed. ASA and SSSA, Madison, WI.

Pearson, R.W. 1966. Soil environment and root development. p. 95–126. *In* W.H. Pierre et al. (ed.) Plant environment and efficient water use. ASA and SSSA, Madison, WI.

Peters, J.M., and N.T. Basta. 1996. Reduction of excessive bioavailable phosphorus in soils by using municipal and industrial wastes. J. Environ. Qual. 25:1236–1241.

Rengasamy, P., J.M. Oades, and T.W. Hancock. 1980. Improvement of soil structure and plant growth by addition of alum sludge. Commun. Soil Sci. Plant Anal. 11:533–545.

Rhoades, J.D. 1982a. Cation exchange capacity. p. 149–157. *In* A.L. Page et al. (ed.) Methods of soil analysis. Part 2. Chemical and biological properties. 2nd ed. ASA and SSSA, Madison, WI.

Rhoades, J.D. 1982b. Soluble salts. p. 167–180. *In* A.L. Page et al. (ed.) Methods of soil analysis. Part 2. Chemical and biological properties. 2nd ed. ASA and SSSA, Madison, WI.

Scambilis, N.A. 1977. Land disposal of chemical sludges. Ph.D. diss., Univ. of Missouri, Columbia.

Schindler, D.W. 1977. The evolution of phosphorus limitation in lakes. Science (Washington, DC) 195:260–262.

Shreve, B.R., P.A. Moore Jr., T.C. Daniel, D.R. Edwards, and D.M. Miller. 1995. Reduction of Phosphorus in runoff from field-applied poultry litter using chemical amendments. J. Environ. Qual. 24: 106–111.

Soltanpour, P.N., J.B. Jones Jr., and S.M. Workman. 1982. p. 55–57. Optical emission spectrometry. *In* A.L. Page et al. (ed.) Methods of soil analysis. Part 2. Chemical and biological properties. 2nd ed. ASA and SSSA, Madison, WI.

Steel, R.G.D., and J.H. Torrie. 1980. Principles and procedures of statistics — A biometrical approach. 2nd ed. McGraw-Hill, New York.

Taylor, G.J. 1991. Current views of the aluminum stress response: The physiological basis of tolerance. p. 57–93. *In* Current topics in plant biochemistry and physiology, 1991. Proc. of the 10th annual Plant Biochemistry and Physiology Symp., Columbia, MO. 4–6 Apr. 1991. Interdisciplinary Plant Biochem. and Physiol. Program., Columbia, MO.

Wisconsin Department of Natural Resources. 1973. Eutrophication control. Nutrient inactivation by chemical precipitation at Horseshoe Lake, Wisconsin. TB62. Dep. of Nat. Resour., Madison, WI.