COMMUN. SOIL SCI. PLANT ANAL., 33(5&6), 831–844 (2002)

COMBINATIONS OF WATER TREATMENT RESIDUALS AND BIOSOLIDS AFFECT TWO RANGE GRASSES

J. A. Ippolito,[1,]* K. A. Barbarick,[1] and E. F. Redente[2]

Departments of [1]Soil and Crop Sciences, and
[2]Rangeland Ecosystem Science, Colorado State University,
Fort Collins, CO, 80523-1170

ABSTRACT

The beneficial reuse of water treatment plant residuals (WTR) and biosolids via land co-application is of concern since the WTR is postulated to greatly reduce plant phosphorus (P) availability and, along with biosolids, possibly provide an additional source of trace metals to soil. Potential plant Al toxicity with increasing WTR rates, because of the Al content of WTR [$Al_2(SO_4)_3 \cdot 14H_2O$], has also been speculated. 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 [*Agropyron smithii* (Rydb.) A. Love]. Co-application rates were a factorial combination of 0, 2.5, 5, 7.5, and 10 g kg^{-1} of WTR and 0, 2.5, 5, 7.5, and 10 g kg^{-1} of biosolids. Increasing WTR rate, averaged over biosolids rate, resulted in a decrease ($p < 0.10$) in blue grama P concentration and an increase in Al concentration. Increasing biosolids rate, averaged over WTR rates, significantly

*Corresponding author. E-mail: ippolito@lamar.colostate.edu

affected most constituents. With only WTR addition (no biosolids) to blue grama, we observed an increase in plant Al concentration and uptake, and a decrease in plant Mo concentration. Increasing WTR rate, averaged over biosolids rate, produced a significant decrease in western wheatgrass P and molybdenum (Mo) concentrations. Increasing biosolids rate, averaged over WTR rates, again affected most constituents studied. With only WTR addition (no biosolids) to western wheatgrass, this study observed a decrease in plant Mo concentration and uptake. In both studies no significant WTR-biosolids interactions were observed. These results indicate WTR could reduce P availability even when co-applied with biosolids. Co-application can aid municipalities dealing with excessive biosolids-borne P and Mo application associated with an agronomic (nitrogen) biosolids application rate. However, high application rates of WTR should be avoided due to its adverse effect on P availability to plants, unless a supplemental P source is supplied.

INTRODUCTION

Alum [$Al_2(SO_4)_3 \cdot 14H_2O$] is commonly used in the municipal drinking water treatment process to destabilize colloids for subsequent flocculation and water clarification. Water treatment residuals (WTR) can be classified as a waste material from municipal drinking water treatment plants, whereas biosolids are a by-product of wastewater treatment plants. Biosolids have been proven effective soil amendments, whereas research of WTR soil addition is still in its infancy.

Most WTR generated via water treatment plants is currently discharged to sanitary sewers, lagooned, or dewatered and disposed in landfills (1). Current environmental concerns over WTR discharge to receiving waters has resulted in this practice being discouraged in many locales(2). Although no federal guidelines exist for water treatment plant effluents, U.S. Environmental Protection Agency (USEPA) regions or individual states can prohibit direct discharge (3).

In the past, the potential benefits of WTR to the soil have generally been considered limited. Cornell and Westerhoff (4) state “attempts to use coagulation sludges as soil conditioners or stabilizers have had little success.” Rengasamy et al.(5), Dempsey et al.(6), and Lin(7), however, report significant levels of N in WTR, which may benefit soil fertility.

The organic matter content of WTR is variable and their addition may or may not benefit the soil. Reports of 3 to 35% average total organic content have been reported for WTR (1,8).

Rengasamy et al. (5) found that adding wet WTR markedly altered the mechanical properties of soils, increasing aggregation and decreasing the modulus of rupture of molded soil briquettes. Scambilis (9) reported increased soil cohesion by alum- and softening-sludge additions.

Changes in soil moisture properties have also been documented. Bugbee and Frink (8) found that improvements in soil moisture holding capacity and aeration from WTR additions were sufficient to offset induced P deficiencies. Rengasamy et al. (5) found that WTR addition increased water retention. Scambilis (9) found that both alum and softening sludges modestly increased soil drainage ability.

Recent investigation into the use of alum as a poultry litter amendment have been documented. Shreve et al. (10)examined the effects of alum addition to poultry litter on P concentrations and load in runoff to evaluate the effects of amended litter on forage (fescue; *Festuca arundinacea* Schreb.) production. They observed decreased P runoff loss and increased forage yields with alum-amended litter compared to non-amended poultry litter. Their results indicated alum-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 economically benefiting poultry producers.

In a separate study, Moore et al. (11) showed addition of alum to poultry litter decreased litter NH_3 volatilization and extractable water-soluble P. Volatilization of NH_3 within poultry houses can be detrimental to humans and birds and water-soluble P is considered to be the primary element of concern with respect to eutrophication of freshwater systems (12). Decreases in volatilization resulted in higher total and soluble N in litter, which increased N/P ratios and resulted in a more valuable fertilizer. This information may potentially benefit municipalities coping with future WTR disposal regulations.

The single most important property of WTR is its ability to adsorb P. Rengasamy et al. (5) found that application of WTR at 45 $Mg\,ha^{-1}$ reduced P uptake and caused yield reductions in maize (*Zea mays* L.). Tissue analysis showed tomato shoots (*Lycopersicon esculentum* L.) (13)and lettuce (*Lactuca sativa* L.) (8) grown in potting media amended with WTR contained significantly lower P levels. Heil and Barbarick (14) applied WTR at rates of 0 to 25 $g\,kg^{-1}$ soil to sorghum–sudangrass [*Sorghum bicolor* (L.) Moench-*Sorghum x drummondii* (Steudel) Millsp. and Chase] grown in two soils in a greenhouse study. Phosphorus deficiencies were observed at the highest rate of WTR. By doubling the P fertilizer added to the highest WTR rate, sorghum–sudangrass produced 29% greater yield, further indicating an adsorption effect by the WTR.

The co-application of WTR and biosolids to land has not been extensively studied. Harris-Pierce et al. (15,16) investigated the effects of WTR and biosolids co-application on aboveground plant biomass of four dominant shortgrass prairie species. No significant trends in the biomass or tissue concentrations of the four species [blue grama (*Bouteloua gracilis* H.B.K. Lag), western wheatgrass (*Agropyron smithii*), buffalograss (*Buchloe dactyloides*), and fringed sage

(*Artemisia frigida*)] were observed in plots treated with WTR rates of 5.6 to 22.4 $Mg\,ha^{-1}$, when combined with 11.2 $Mg\,ha^{-1}$ of biosolids. In a greenhouse study, Ippolito et al. (17) co-applied variable rates of WTR with a constant biosolids rate to blue grama and western wheatgrass. They observed increased blue grama yield and decreasing P and Al plant concentrations with increasing WTR rate. They also observed a decrease in western wheatgrass Al concentration with increasing WTR rate.

Our objectives were to (1) quantify the effects of a factorial co-application of WTR and biosolids on biomass production of blue grama and western wheatgrass and (2) determine co-application effects on P, Al, and Mo plant concentrations and uptake. Phosphorus was considered because of the WTR's Al hydroxide P-fixing properties, Al due to the concern for potential plant toxicity, and Mo because of the subsequent WTR interaction or dilution effect on Mo concentration in biosolids as compared to the USEPA (18) 40 CFR Part 503 regulations.

MATERIALS AND METHODS

The WTR and biosolids were obtained from the city of Fort Collins, CO drinking water and wastewater treatment facilities, respectively. The soil was obtained (an Altvan sandy loam; fine-loamy over sandy or sandy-skeletal, mixed, mesic, Aridic Argiustoll; pH 6.9) from the city of Fort Collins, CO Meadow Springs Ranch, a parcel of land used for beneficial reuse of biosolids. We determined total elemental composition of the soil, WTR, and biosolids by a modified $HClO_4$–HNO_3–HF–HCl digestion (Table 1) (19) and analyzed the digestate using inductively coupled plasma-atomic emission spectroscopy (ICP-AES). Total N was determined by a H_2SO_4 digestion (20). The NO_3-N and NH_4-N were determined using a 2 *M* KCl extract (21), pH and EC using a saturated paste extract (22,23), organic matter content using the Walkley–Black procedure (24), and CEC via the Rhoades method (25).

Blue Grama

Ten blue grama plants were germinated in 10-cm diameter by 33-cm tall PVC pots containing 2.5 kg of the Altvan soil. Co-application rates were a factorial combination of 0, 2.5, 5, 7.5, and 10 $g\,kg^{-1}$ of WTR and 0, 2.5, 5, 7.5, and 10 $g\,kg^{-1}$ of biosolids. All applications were manually mixed into the top 2.5 to 5.0 cm of soil. A randomized complete block experimental design with four replications was utilized.

After the plants were established (approximately 8 weeks after initial planting), pots were irrigated to field capacity (26% moisture) two to three times

Table 1. Selected Chemical Characteristics of Soil, WTR, and Biosolids Used in the Greenhouse Experiment

Element (Unit)	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 ($g\,kg^{-1}$)	0.1	0.2	0.6
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 ($g\,kg^{-1}$)	0.3	0.8	0.1
Ti ($g\,kg^{-1}$)	0.7	0.8	0.1
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 ($mg\,kg^{-1}$)	9.2	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 ($mg\,kg^{-1}$)	464.0	322.0	125.0
V ($mg\,kg^{-1}$)	35.6	34.3	14.9
Total N (%)	0.1	0.4	5.6
NH_4-N ($mg\,kg^{-1}$)	8.8	70.1	25,000
NO_3-N	1.0	44.0	9.2
pH	6.9	6.9	7.7
EC($dS\,m^{-1}$)	0.2	0.7	11.2
O.M. (%)	1.7	6.3	ND
CEC (cmol(+) kg^{-1})	11.8	39.3	ND

per week, and plants were thinned to six plants per pot. The removed plants were placed back into the pots as to not lose any material.

To promote vegetative growth, we removed emerging seed heads off plants and placed the seed heads back into each pot. The blue grama plants were harvested at a height of 2.5 cm, rinsed the plants with distilled water, dried at 70°C for at least 48 hours, and were weighed. Plants were ground to pass a 20-mesh sieve. A subsample was digested in concentrated HNO_3 and analyzed for P, Al, and Mo using ICP-AES (26). Plant elemental uptake was determined by multiplying elemental concentration by dry matter yield. Analyses of variance was performed on the data, assuming significant effects if the probability level (p) was <0.10 (27).

Western Wheatgrass

Co-application rates, the number of plants germinated, and experimental design were similar to blue grama.

After the plants were established (approximately 8 weeks after initial planting), pots were irrigated to field capacity (26% moisture) two to three times per week, and plants were thinned to four plants per pot. Removed plants were placed back into the pots. Seed heads were also removed to promote vegetative growth, and placed back into pots. Plants were harvested at a height of 2.5 and subsequent analyses was similar to blue grama.

RESULTS AND DISCUSSION

Blue Grama

Increasing WTR rate, averaged over biosolids rates, significantly ($p < 0.10$) decreased blue grama P concentration and increased Al concentration (Table 2). The high P adsorptive capacity of WTR (14,17) limited P availability even when a secondary source of P (i.e., biosolids) was co-applied. The WTR's chemical composition [$Al_2(SO4)_3 \cdot 14H_2O$] likely caused the increase in plant Al concentration. Increasing the WTR rate, averaged over biosolids rates, did not affect dry matter yield, P and Al uptake, or Mo concentration and uptake.

Increasing the biosolids application rate, averaged over WTR rates, affected most constituents studied due to the amount of necessary and trace elements contained in the biosolids (Table 2). The maximum tolerable plant levels of dietary minerals for domestic animals range from 0.8–1.5% for P, 200–1000 mg kg^{-1} for Al, and 5–100 mg kg^{-1} for Mo (28). Our plant concentrations fell well below these tolerable levels. Also, there were no observable interaction effects between WTR and biosolids.

The effects of WTR alone (without biosolids) on dry matter yields and plant P, Al, and Mo concentrations and uptake are shown in Table 3. Although we do not recommend applying WTR alone due to lack of N for plant growth, we present the data to illustrate the effects. Increasing WTR rate caused increased Al concentration and uptake ($p < 0.10$). The Al content most likely increased due to WTR's chemical composition. There were no significant effects on dry matter yield, or P and Mo concentration or uptake.

Table 2. Effects of WTR and Biosolids on Blue Grama Dry Matter Yields and Plant P, Al, and Mo Concentrations and Uptake

WTR ($g\,kg^{-1}$)	Biosolids ($g\,kg^{-1}$)	Dry Matter Yields ($g\,pot^{-1}$)	P Concentration ($g\,kg^{-1}$)	P Uptake ($mg\,pot^{-1}$)	Al Concentration ($mg\,kg^{-1}$)	Al Uptake ($\mu g\,pot^{-1}$)	Mo Concentration ($mg\,kg^{-1}$)	MO Uptake ($\mu g\,pot^{-1}$)
Average over biosolids								
0		7.3	2.3	17	16	118	0.64	4.7
2.5		7.9	2	15	16	126	0.69	5.2
5		7	2.1	14	16	116	0.69	4.8
7.5		7.5	1.9	14	15	115	0.66	4.7
10		8.0	1.9	14	19	152	0.75	6
			ANOVA	Probability	Level	(p)		
WTR		*0.742*	*0.075*	*0.136*	*0.044*	*0.189*	*0.444*	*0.262*
Average over WTR								
	2.5	*6.6*	*1.6*	*11*	*15*	*99*	*0.53*	*3.4*
	5.0	*8.7*	*1.9*	*15*	*17*	*146*	*0.59*	*5.1*
	7.5	*8.5*	*2.2*	*18*	*18*	*156*	*0.75*	*6.3*
	10	*6.4*	*2.6*	*15*	*16*	*102*	*0.88*	*5.5*
			ANOVA	Probability	Level	(p)		
Biosolids		*0.002*	*0.000*	*0.000*	*0.106*	*0.000*	*0.000*	*0.000*
Interaction			ANOVA	Probability	Level	(p)		
WTR × biosolids		*0.768*	*0.778*	*0.244*	*0.552*	*0.939*	*0.533*	*0.827*

Western Wheatgrass

Increasing WTR rate, averaged over biosolids rates, significantly ($p < 0.10$) reduced plant P and Mo concentrations (Table 4). The reduction in plant P may be due to WTR's adsorption of P. Even though P concentrations decreased with increasing WTR, we did not observe any P-deficiency symptoms. The decrease in Mo concentration may be due to a dilution effect or an interaction with WTR-borne Al. Water treatment residuals tend to have large quantities of amorphous Al oxides and hydroxides. And as with soils that are high in Fe and Al, especially noncrystalline Fe and Al forms on clay surfaces, the availability of Mo tends to be low (29). Increasing WTR rate did not affect dry matter yields, P uptake, Al concentration or uptake, or Mo uptake.

Biosolids rate, averaged over WTR rates, again affected most constituents studied (Table 4). This was due to addition of elements associated with biosolids application. Also, we found no significant interactions between WTR and biosolids application rates.

The effect of WTR alone (without biosolids) on dry matter yields and plant P, Al, and Mo concentrations and uptake are shown in Table 5. Again, applying WTR alone is not recommended due to the lack of N for plant growth. However, we present the data to illustrate WTR effects. Increasing the WTR rate caused a decrease in plant Mo concentration and uptake. The WTR rate alone did not significantly affect dry matter yields, or P and Al concentration or uptake. The decrease in both Mo concentration and uptake again may be due to a Mo interaction with WTR-borne Al.

CONCLUSIONS

Our results indicate that WTR can reduce P availability to blue grama and western wheatgrass even when co-applied with biosolids which provide plant-available P. Heil and Barbarick (14) have reported that application of WTR to soils could decrease plant available P while having little effect on trace element availability. Consequently, high application rates of WTR should be avoided due to its adverse effect on biosolids-borne P, and possible soil P availability.

In addition, increasing WTR rate, averaged over biosolids rates, produced an increase in blue grama Al concentration and a decrease in western wheatgrass Mo concentration. The increase in blue grama Al concentration is most likely due to the chemical composition of WTR used in this study. The decrease in western wheatgrass Mo concentration may be attributable to a dilution affect or Mo interaction with WTR-borne Al.

For illustrative purposes, we presented the effect of WTR alone (without biosolids application) on dry matter yields and plant P, Al, and Mo concentration

Table 3. Effects of WTR Alone (Without Biosolids) on Blue Grama Dry Matter Yields and Plant P, Al, and Mo Concentrations and Uptake

WTR ($g\,kg^{-1}$)	Dry Matter ($g\,pot^{-1}$)	P Concentration ($g\,kg^{-1}$)	P Uptake ($mg\,pot^{-1}$)	Al Concentration ($mg\,kg^{-1}$)	Al Uptake ($\mu g\,pot^{-1}$)	Mo Concentration ($mg\,kg^{-1}$)	Mo Uptake ($\mu g\,pot^{-1}$)
0	1.9	1.62	3.2	14	27	2.98	4.6
2.5	1.7	1.72	2.8	21	34	0.76	1.1
5	1.9	1.72	3.2	21	37	0.58	1.1
7.5	2.4	2.02	4.7	22	56	0.42	1.0
10	2.1	1.55	3.3	25	52	0.51	1.0
		ANOVA	Probability	Level	(p)		
	0.271	*0.821*	*0.442*	*0.046*	*0.025*	*0.129*	*0.164*

Table 4. Effects of Alum and Biosolids on Western Wheatgrass Dry Matter Yields and Plant P, Al, and Mo Concentrations and Uptake

WTR ($g\,kg^{-1}$)	Biosolids ($g\,kg^{-1}$)	Dry Matter Yields ($g\,pot^{-1}$)	P Concentration ($g\,kg^{-1}$)	P Uptake ($mg\,pot^{-1}$)	Al Concentration ($mg\,kg^{-1}$)	Al Uptake ($\mu g\,pot^{-1}$)	Mo Concentration ($mg\,kg^{-1}$)	Mo Uptake ($\mu g\,pot^{-1}$)
Average over biosolids								
0		13.6	1.7	22	22	324	0.59	8.3
2.5		14.4	1.3	19	24	339	0.55	7.9
5		12.1	1.8	17	17	229	0.45	5.3
7.5		13.5	1.4	17	22	316	0.39	5.3
10		13.8	1.4	18	19	284	0.42	5.6
			ANOVA	Probability	Level	(p)		
WTR		*0.76*	*0.06*	*0.26*	*0.14*	*0.14*	*0.03*	*0.14*
Average over WTR								
	2.5	*10.1*	*1.1*	*11*	*19*	*193*	*0.42*	*4.1*
	5	*14.9*	*1.3*	*18*	*23*	*352*	*0.44*	*6.5*
	7.5	*15.8*	*1.5*	*22*	*22*	*369*	*0.44*	*6.8*
	10	*13.1*	*2.2*	*25*	*18*	*280*	*0.62*	*8.4*
			ANOVA	Probability	Level	(p)		
Biosolids		*0.003*	*0.000*	*0.000*	*0.192*	*0.029*	*0.008*	*0.029*
Interaction			ANOVA	Probability	Level	(p)		
WTR × biosolids		*0.999*	*0.654*	*0.947*	*0.657*	*0.908*	*0.507*	*0.908*

Table 5. Effects of WTR Alone (Without Biosolids) on Western Wheatgrass Dry Matter Yields and Plant P, Al, and Mo Concentrations and Uptake

WTR ($g\,kg^{-1}$)	Dry Matter ($g\,pot^{-1}$)	P Concentration ($g\,kg^{-1}$)	P Uptake ($mg\,pot^{-1}$)	Al Concentration ($mg\,kg^{-1}$)	Al Uptake ($\mu g\,pot^{-1}$)	Mo Concentration ($mg\,kg^{-1}$)	Mo Uptake ($\mu g\,pot^{-1}$)
0	2.6	1.20	3.1	22	57	0.46	1.2
2.5	2.8	1.05	2.9	26	73	0.53	1.5
5	3.5	1.26	4.4	17	60	0.43	1.5
7.5	3.1	1.13	3.5	14	43	0.41	1.3
10	3.3	1.03	3.4	19	63	0.38	1.3
		ANOVA	Probability	Level	(p)		
	0.176	*0.456*	*0.241*	*0.273*	*0.362*	*0.038*	*0.050*

and uptake. We observed an increase in blue grama Al concentration and uptake and a decrease in western wheatgrass Mo concentration and uptake. The increase in blue grama Al content was most likely due to the chemical composition and increase in WTR rate. The decrease in western wheatgrass Mo content may be due to reaction with amorphous Al hydroxides which are indigenous in WTR.

Biosolids Mo concentration may pose a challenge for beneficial-use programs. The USEPA 40 CFR Part 503 regulations are the basis for biosolids land application and beneficial reuse. The pollutant concentration of biosolids-borne Mo limits were deleted from the 40 CFR 503 regulations pending further Mo research and investigation by the USEPA. Consequently, biosolids users currently must adhere to ceiling biosolids Mo concentrations for land application set by the USEPA. From our study it appears that WTR can reduce the plant-available Mo concentration via dilution or WTR interaction. Although we do not condone the "solution to pollution is dilution" philosophy, our findings are interesting in lieu of the above information.

Land application of biosolids are typically based on the N needs of the plant grown. However, agronomic biosolids N rates may oversupply P. Co-application of WTR and biosolids can reduce the amount of biosolids-borne P via WTR P adsorption. This, as well as landfill avoidance, can benefit municipalities with both waste products. If high WTR application rates are necessary, supplemental P should be co-applied to offset P adsorption.

ABBREVIATIONS

USEPA	US Environmental Protection Agency
ICP-AES	inductively coupled plasma-atomic emission spectroscopy
p	probability level
WTR	water treatment residuals

REFERENCES

1. Elliott, H.A.; Dempsey, B.A.; Hamilton, D.W.; DeWolfe, J.R. *Land Application of Water Treatment Sludges*; Final Report AWWARF: Denver, CO, 1990.
2. Lucas, J.B.; Dillaha, T.A.; Reneau, R.B.; Novak, J.T.; Knocke, W.R. Alum Sludge Land Application and Its Effect on Plant Growth. J. AWWA **1994**, *86*, 11–75.
3. AWWA Sludge Disposal Committee; Committee Report: Research Need for Alum Sludge Discharge. J. AWWA **1987**, *79*, 6–99.

4. Cornell, D.A.; Westerhoff, G.P. Management of Water Treatment Plant Sludges. In *Sludge and Its Ultimate Disposal*; Borchardt, J.A., Ed.; Ann. Arbor Sci. Publishers: Ann Arbor, MI, 1981.
5. Rengasamy, P.; Oades, J.M.; Hancock, T.W. Improvement of Soil Structure and Plant Growth by Addition of Alum Sludge. Commun. Soil Sci. Plant Anal. **1980**, *11*, 533–545.
6. Dempsey, B.A.; DeWolfe, J.; Hamilton, D.; Lee, Y.; Liebowitz, R.; Elliott, H.A. Land Application of Water Plant Sludges. *Proceedings of 44th Purdue Industrial Waste Conference*; Purdue University: West Lafayette, IN, 1989.
7. Lin, S. *Effects of Alum Sludge Application on Corn and Soybeans*; Joint Conf. CSCEASCE, Natl. Conf. of Envir. Engrs. Vancouver, BC, 1988.
8. Bugbee, G.J.; Frink, C.R. *Alum Sludge as a Soil Amendment: Effects on Soil Properties and Plant Growth*; Bull. 823, Conn. Agricultural Exp. Station: Storrs, CT, 1985.
9. Scambilis, N.A. Land Disposal of Chemical Sludges Ph.D. DissertationUniversity of Missouri Columbia, MO.
10. Schreve, B.R.; Moore, P.A., Jr.; Daniel, T.C.; Edwards, D.R.; Miller, D.M. Reduction of Phosphorus in Runoff from Field-Applied Poultry Litter Using Chemical Amendments. J. Environ. Qual. **1995**, *24*, 106–111.
11. Moore, P.A., Jr; Daniel, T.C.; Edwards, D.R.; Miller, D.M. Effect of Chemical Amendments on Ammonia Volatilization from Poultry Litter. J. Environ. Qual. **1995**, *24*, 293–300.
12. Schindler, D.W. The Evolution of Phosphorus Limitation in Lakes. Science **1977**, *195*, 260–262.
13. Elliott, H.A.; Singer, L.M. Effect of Water Treatment Sludge on Growth and Elemental Composition of Tomato Shoots. Commun. Soil Sci. Plant Anal. **1988**, *19*, 345–354.
14. Heil, D.M.; Barbarick, K.A. Water Treatment Sludge Influence on the Growth of Sorghum–sudangrass. J. Environ. Qual. **1989**, *18*, 292–298.
15. Harris-Pierce, R.; Barbarick, K.A.; Redente, E.F. *The Effect of Sewage Sludge Application on Native Rangeland Soils and Vegetation, Fort Collins Meadow Springs Ranch*; City of Fort Collins: CO, 1993; Annual Report
16. Harris-Pierce, R.; Barbarick, K.A.; Redente, E.F. *The Effect of Sewage Sludge Application on Native Rangeland Soils and Vegetation*, *Fort Collins Meadow Springs Ranch*; City of Fort Collins, CO, 1994; Annual Report.
17. Ippolito, J.A.; Barbarick, K.A.; Redente, E.F. Co-Application Effects of Water Treatment Residuals and Biosolids on Two Range Grasses. J. Environ. Qual. **1999**, *28*, 1644–1650.
18. USEPA; Standards for the Use or Disposal of Sewage Sludge. Fed. Regist. **1993**, *58*, 9248–9415.
19. Soltanpour, P.N.; Johnson, G.W.; Workman, S.M.; Jones, J.B., Jr.; Miller, R.O. Inductively Coupled Plasma Emission Spectrometry and Inductively

Coupled Plasma-Mass Spectrometry. In *Methods of Soil Analysis. Part 3. Chemical Methods*; Sparks, D.L., Ed.; Soil Science Society of America: Madison, WI, 1996; 91–139.

20. Bremner, J.M. Nitrogen: Total. In *Methods of Soil Analysis, Part 3. Chemical Methods*; Sparks, D.L., Ed.; Soil Science Society of America: Madison, WI, 1996; 1085–1121.
21. Mulvaney, R.L. Nitrogen: Inorganic Forms. In *Methods of Soil Analysis. Part 3. Chemical Methods*; Sparks, D.L., Ed.; Soil Science Society of America: Madison, WI, 1996, 1123–1184.
22. Thomas, G.W. Soil pH and Soil Acidity. In *Methods of Soil Analysis. Part 3. Chemical Methods*; Sparks, D.L., Ed.; Soil Science Society of America: Madison, WI, 1996; 475–490.
23. Rhoades, J.D. Salinity: Electrical Conductivity and Total Dissolved Solids. In *Methods of Soil Analysis. Part 3. Chemical Methods*; Sparks, D.L., Ed.; Soil Science Society of America: Madison, WI, 1996; 417–435.
24. Nelson, D.W.; Sommers, L.E. Total Carbon, Organic Carbon, and Organic Matter. In *Methods of Soil Analysis. Part 3. Chemical Methods*; Sparks, D.L., Ed.; Soil Science Society of America: Madison, WI, 1996; 961–1010.
25. Rhoades, J.D. Cation Exchange Capacity. In *Methods of Soil Analysis. Part 3. Chemical Methods*; Sparks, D.L., Ed.; Soil Science Society of America: Madison, WI, 1996; 149–157.
26. Havlin, H.L.; Soltanpour, P.N. A Nitric Acid Plant Tissue Digest Method for Use with Inductively Coupled Plasma Spectrometry. Commun. Soil Sci. Plant Anal. **1980**, *11*, 969–980.
27. Steel, R.G.D.; Torrie, J.H. *Principles and Procedures of Statistics—A Biometrical Approach*, 2nd Ed.; McGraw-Hill, Inc.: New York, 1980.
28. National Research Council, *Mineral Tolerance of Domestic Animals*; National Academy of Sciences: Washington, DC, 1980; 577.
29. Tisdale, S.L.; Nelson, W.L.; Beaton, J.D. *Soil Fertility and Fertilizers*, 4th Ed.; Macmillan Publishing Co.: New York, 1985.