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Growth of Forage Legumes and Grasses in Acidic Soil Amended with Flue Gas Desulfurization Products

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ABSTRACT

Large amounts of flue gas desulfurization products (FGDs) are produced when SO₂ emissions are trapped in the coal burning process for generation of electricity. FGDs are normally discarded instead of being reused, and reuse on soils could be important in overall management of these products. Glasshouse experiments were conducted to determine effects of various levels of three FGDs (a FGD gypsum, an oxidized FGD + Mg, and a stabilized FGD) and the control compounds CaCO₃, CaSO₃, and CaSO₄ on growth of alfalfa (*Medicago sativa*), white clover (*Trifolium repens*), orchardgrass (*Dactylis glomerata*), tall fescue (*Festuca arundinacea*), switchgrass (*Panicum virgatum*), and eastern gamagrass (*Tripsacum dactyloides*) in acidic (pH 4) soil (Typic

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Hapludult). The FGDs enhanced growth of each plant species, with alfalfa, white clover, and tall fescue receiving greater increases than the other species, especially when grown in soil amended with FGD + Mg. FGD gypsum did not often enhance growth unless high amounts were added. FGDs containing high B and low levels of CaSO_3 were detrimental to growth. Overall, FGDs improved growth responses of these forage plants grown in an infertile low pH soil.

INTRODUCTION

Many coal combustion products (CCPs), especially flue gas desulfurization products (FGDs), are produced when coal is burned for generation of electricity. Generation of FGDs results by trapping sulfur dioxide (SO_2) from flue gases, which is accomplished by injecting Ca based sorbents, particularly limestone, to form $\text{CaSO}_3/\text{CaSO}_4$. Most FGDs as well as other CCPs are discarded into landfills, even though many could be reused. In the United States, a 1999 survey indicated that only 10% of FGDs were being reused in 1998.^[1] Uses of FGDs could be as an amendment to soils, especially acidic soils, for increasing soil pH to alleviate plant mineral toxicities [e.g., aluminum (Al) and manganese (Mn)] and deficiencies [e.g., calcium (Ca), phosphorus (P), and magnesium (Mg)]; for providing a source of mineral nutrients to plants [e.g., Ca, sulfur (S), Mg, boron (B), zinc (Zn), and molybdenum (Mo)]; for improving soil water infiltration, water-holding capacity, and aggregation; for reducing soil crusting and erosion; for reducing P run-off from high-P surface soils into streams and estuaries; and for co-utilizing with organic/compost materials.^[2–13] Use of FGDs on land could be important in overall management of these products.

Information about FGD effects on plant growth needs to be evaluated if these products are to be reused on land. The FGDs formed are normally slurries consisting mainly of CaSO_3 , and other solid materials like fly ash, calcined lime [CaO and Ca(OH)_2], and/or additional limestone are commonly added to stabilize such products. Unreacted or added limestone and $\text{CaO}/\text{Ca(OH)}_2$ are alkalizing agents which can increase pH when mixed with soil. In some cases, CaSO_3 is converted directly to CaSO_4 (CaSO_4 is used throughout the text for $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ and/or $\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$) through processes such as “forced oxidation” to form gypsum.

Information about the effects of FGDs on growth of plants is limited. In glasshouse studies, maize (*Zea mays* L.) was grown in acidic soil amended with various types of FGDs to determine their effects on growth and on soil pH

and electrical conductivity (EC).^[14,15] In these studies, some FGDs were very effective in enhancing growth and improving soil pH, while others were not. Plants grown in unamended soil consistently had relatively severe growth inhibitions, and these inhibitions were alleviated to some extent by applications of FGD. Of the FGDs tested, one particularly benefited plants at low levels of application, which was a FGD + Mg product. Another FGD decreased growth at application levels of less than 5% (to convert percentage values in soil mixes to metric tons ha⁻¹ multiply by 22) in soil mixes, but such growth inhibitions were overcome as level increased. Most FGDs (non-stabilized and stabilized) could be added only at low levels (1–3%) in soil mixes, while oxidized FGDs (FGD gypsum) could be added at high levels (50–75%) in soil mixes.

A FGD gypsum product increased coastal bermudagrass [*Cynodon dactylon* (L.) Pers.] yields over two years by 26 and 35%, respectively, with 0.25 and 0.5 metric ton ha⁻¹ applications to soil.^[16] Addition of the FGD had no significant effects on soil pH although the highest level had slight acidifying effects at various soil depths. Alfalfa (*Medicago sativa* L.) grown over two years in acidic soil amended with a FGD gypsum product had yield increases of 14% over controls at the highest level (18 metric ton ha⁻¹) added.^[17] Growth increases were attributed to decreased soil Al and not from increased acquisition of mineral nutrients. Citrus (*Citrus* spp.) grown in sandy soil with low extractable Ca at two locations had increased fruit yields, fruit soluble solids, and leaf Ca (one location) when FGD gypsum was applied at 2.24, but not 1.12, metric ton ha⁻¹.^[18] In a glasshouse study, Punshon et al.^[19] did not find enhanced growth when maize was grown in soil mixed with various levels of a FGD. However, maize, soybean [*Glycine max* (L.) Merr.], cotton (*Gossypium hirsutum* L.), and radish (*Raphanus sativus* L.) grown in mesocosms (tanks in the field) had enhanced growth when this same FGD was added to soil, and plant species differed in level of FGD required to produce maximum plant dry matter.^[19]

Enhanced alfalfa (*Medicago sativa* L.) and tall fescue (*Festuca arundinacea* Schreb.) growth in glasshouse studies were noted when dry FGDs [fluidized bed combustion (FBC) products] were applied, and alfalfa produced greater yields than tall fescue.^[20] In field studies, a FBC + Mg product enhanced growth of alfalfa, but not maize.^[21]

The objective of our studies was to determine effects of different levels of three FGDs added to acidic soil on growth of six forage species. These plants were also grown in acidic soil amended with different levels of the control compounds CaCO₃, CaSO₃, and CaSO₄ for comparison to FGDs. The effects

of added FGDs and control compounds on soil pH and EC have also been related to growth.

MATERIALS AND METHODS

An acidic Lily soil (fine loamy, siliceous, mesic, Typic Hapludult) was used, and some of its properties before addition of amendments were: 43.1% sand, 38.8% silt, and 18.2% clay; 4.70% organic matter; 4.48 pH_W (1 soil:1 water) and 3.89 pH_{Ca} (1 soil:1 10 mM CaCl₂); 0.06 dS m⁻¹ EC; 3.09 P in mg kg⁻¹ soil (Bray-1 extractable); 70.0 S, 69.5 K, 45.8 Ca, 5.06 Mg, and 2.30 Na in mg kg⁻¹ soil (1 M NH₄-acetate extractable); 53.8 Fe, 33.1 Mn, 0.716 Zn, 0.125 Cu in mg kg⁻¹ soil (5 mM DTPA extractable); 3.36 Al in cmol_c kg⁻¹ soil (1 M KCl extractable); 3.82 cation exchange capacity in cmol_c kg⁻¹ soil; and 88.0% Al saturation of cation exchange capacity.

Air-dried soil was passed through a 2 mm screen, mixed thoroughly with fertilizer (50 N as NH₄NO₃ and 143 P as KH₂PO₄ in mg kg⁻¹ soil) and various levels of control compounds (chemical grade CaCO₃, CaSO₃, and CaSO₄) or FGDs, and soil mixes placed in plastic containers (1.0 kg soil mix pot⁻¹). See data tables for levels of each material added to soil mixes. Levels of control substances and FGDs added to soil were to achieve both growth enhancements and depressions as established in earlier studies (unpublished data).^[14] Levels of CaSO₃ and FGD-28 (stabilized FGD) added to soil were similar as both of these materials had high SO₃-S, and levels of CaSO₄ and FGD-22 (FGD gypsum) were similar as both of these materials had high SO₄-S. FGD-27 was a FGD + Mg product. Some selected properties of the FGDs are provided in Table 1.

The plant species used in the experiments were two legumes [alfalfa (*Medicago sativa* L. cv. 'Vernal') and white clover (*Trifolium repens* L. cv. 'Huia')], two cool-season grasses [orchardgrass (*Dactylis glomerata* L. cv. 'Wana') and tall fescue (*Festuca arundinacea* Schreb. cv. 'KY31')], and two warm-season grasses [switchgrass (*Panicum virgatum* L. cv. 'Cave-in-Rock') and eastern gamagrass (*Tripsacum dactyloides* L. cv. 'WW1459')]. Seeds of each plant species were surface-sterilized with 0.1-strength NaOCl (household bleach) for 5 min and rinsed thoroughly with distilled water. Six to eight seeds were planted in each pot of moist soil, seedlings were allowed to establish, and thinned to three pot⁻¹ a few days after seedling emergence. Deionized water was added manually as needed to avoid splashing on stalks and leaves and to provide sufficient water for growth. Care was taken to avoid leaching from pots. Minor leaching occurred sometimes from some pots when plants did not grown well. Nevertheless, soil pH and EC values after amendment addition

Table 1. Selected properties of FGDs used to amend acidic soil^a.

Property	Unit	FGD-22	FGD-27	FGD-28
pH (1 FGD:1 water)		8.91	9.53	8.68
pH (1 FGD:2 water)		8.96	9.65	8.82
EC (1 FGD:1 water)	dS m ⁻¹	1.67	3.35	5.58
EC (1 FGD:2 water)	dS m ⁻¹	1.92	3.29	4.17
CCE ^b	%	5.0	13.1	69.3
Chemical element				
S-SO ₃	g kg ⁻¹	0.8	1.0	25.9
S-SO ₄	g kg ⁻¹	216	176	200
Ca	g kg ⁻¹	238	209	509
Mg	g kg ⁻¹	0.23	22.7	24.4
K	mg kg ⁻¹	32	165	88
P	mg kg ⁻¹	60.7	<0.03	90.7
B	mg kg ⁻¹	<0.02	99.0	7.81

^a Additional properties of FGD-22 (BP-#22) and FGD-27 (BP-#27) are reported in Clark et al.^[14]

^b CCE = Calcium carbonate equivalency.

and equilibrium had similar values to soils after plant growth, thus, any minor leaching appeared to have no effect on soil pH and EC.

Plants were grown in a glasshouse ($25 \pm 3^\circ\text{C}$) using natural and artificial light to maintain the light period at 14 h and to provide extra light during cloudy days. Artificial light ($400\text{--}500 \mu\text{mol m}^{-2} \text{s}^{-1}$ photo flux density at plant height) was provided by high-pressure Na lamps. Because of the large number of treatments and plant species, experiments were conducted over a period of time and each species was grown at least in two experiments, except alfalfa which was grown in only one experiment. Growth periods for each plant species were 82 d for alfalfa, 59 d for white clover, 55 d for orchardgrass, 54 d for tall fescue, 69 d for switchgrass, and 71 d for eastern gamagrass.

At harvest, shoots were severed ~ 1 cm above the soil surface or ~ 0.5 cm above the crown. Representative soil samples were collected from each pot for determination of soil pH_{Ca} (1 soil:1 10 mM CaCl₂) and EC (1 soil:1 water). Soil with roots was placed on 2 mm screens and roots thoroughly washed free of adhering soil. Crowns were separated from root segments and shoots and crowns were dried separately at 60°C, after which they were weighed for dry matter (DM). Roots from each pot were cut into ~ 2 cm length segments,

thoroughly mixed, and fresh weight subsamples (5–10 g) were collected for determination of root length (RL) using a Comair RL scanner (Commonwealth Aircraft Corp. Ltd., Melbourne, Australia^a). Remaining roots and root subsamples for RL determinations were dried separately similar to shoots and weighed. Total shoot (shoots + crowns) and root DM were determined. Specific RL (SRL) was calculated as length of roots (m) per g root DM.

The experimental design was completely randomized blocks with four replications, except for alfalfa which had six replications. Least significance differences (LSD) at $P < 0.05$ were used to evaluate differences among means.^[22]

RESULTS

Soil pH_{Ca} And EC

Soil pH_{Ca} and EC values were averaged over soils in which the various plant species were grown with added control compounds and FGDs (Table 2), since values were similar across similar treatments. Soil pH_{Ca} (3.9 in unamended soil) increased as expected when soil was amended with CaCO₃, and was > 5.5 at the 0.5% level in the soil mixes. Increasing levels of CaSO₃ or CaSO₄ had little effect on soil pH_{Ca}. In fact, CaSO₄ at 75% in soil mixes increased soil pH_{Ca} by only 0.4–0.5 units. FGD-22 increased soil pH_{Ca} to ~ 7 at high levels of addition (75%). Level of FGD-28 required to raise soil pH_{Ca} to ~ 5 was 3%, and level of FGD-27 required to raise soil pH_{Ca} to ~ 7 was 10%.

CaCO₃ had essentially no effect on increasing soil EC, but both CaSO₃ and CaSO₄ did. Soil EC was 0.10 dS m^{-1} in unamended soil and increased to 1.05 dS m^{-1} with 5% added CaSO₄ (10-fold increase), and soil EC remained relatively constant with additional 15-fold increases in level of CaSO₄ added to soil. Soil EC consistently increased as level of CaSO₃ increased. FGD-22 added to soil had similar effects on EC as CaSO₄, in that EC remained relatively constant with successive incremental increases of FGD-22. On the other hand, both FGD-27 and FGD-28 increased soil EC consistently as their level increased in soil.

^aMention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

Table 2. pH_{Ca} and electrical conductivity (EC) values for acidic Lily soil after amendment with various levels of CaCO₃, CaSO₃, CaSO₄, and three FGDs (means after growth of six plant species).

Treatment	Level (% in Soil)	pH _{Ca}	EC (dS m ⁻¹)
Control	0	3.93 ± 0.08	0.10 ± 0.02
CaCO ₃	0.125	4.46 ± 0.08	0.10 ± 0.03
	0.25	4.98 ± 0.10	0.14 ± 0.05
	0.5	5.44 ± 0.50	0.19 ± 0.09
CaSO ₃	0.25	4.21 ± 0.07	0.79 ± 0.27
	0.5	4.24 ± 0.11	1.22 ± 0.45
	1.0	4.30 ± 0.15	2.19 ± 0.84
	2.0	4.40 ± 0.10	4.56 ± 1.22
	3.0	4.48 ± 0.05	6.92 ± 1.42
CaSO ₄	5	4.16 ± 0.04	1.05 ± 0.29
	10	4.19 ± 0.05	1.05 ± 0.15
	25	4.24 ± 0.07	1.12 ± 0.08
	50	4.28 ± 0.07	1.16 ± 0.07
	75	4.40 ± 0.06	1.06 ± 0.07
FGD-22	5	4.44 ± 0.12	1.06 ± 0.09
	10	4.86 ± 0.17	1.10 ± 0.05
	25	6.28 ± 0.14	1.17 ± 0.08
	50	6.89 ± 0.14	1.24 ± 0.05
FGD-27	75	7.02 ± 0.13	1.24 ± 0.08
	1.0	4.33 ± 0.11	1.02 ± 0.14
	2.5	4.82 ± 0.16	1.46 ± 0.16
	5.0	5.65 ± 0.16	1.93 ± 0.14
	10	6.73 ± 0.13	2.25 ± 0.11
FGD-28	25	7.85 ± 0.14	2.50 ± 0.16
	0.25	4.09 ± 0.10	0.28 ± 0.09
	0.5	4.14 ± 0.10	0.46 ± 0.10
	1.0	4.20 ± 0.10	0.76 ± 0.13
	2.0	4.49 ± 0.14	1.19 ± 0.16
	3.0	5.01 ± 0.15	1.46 ± 0.11

Plant Growth

Legumes

The alfalfa cultivar grew very poorly in unamended acidic soil compared to the white clover cultivar (Tables 3 and 4). Both legumes grew quite well

Table 3. Alfalfa shoot, root, and total dry matter (DM), shoot/root (S/R) DM ratio, and total and specific root lengths when grown in acidic soil amended with various levels of CaCO_3 , CaSO_3 , CaSO_4 , and three FGDs.

Treatment	Level (% in soil)	Plant dry matter (mg plant ⁻¹)				Root length	
		Shoots	Roots	Total	S/R DM ratio	Total (m plant ⁻¹)	Specific (m g ⁻¹ DM)
Control	0	3.7	4.6	8.3	0.80	0.5	118
CaCO ₃	0.133	198	418	616	0.48	41.0	100
	0.25	325	668	993	0.48	40.4	60
CaSO ₃	0.5	347	649	996	0.55	26.0	52
	0.25	9.2	14.3	23.5	0.65	1.7	119
	0.5	7.3	9.2	16.5	0.78	1.1	118
	1.0	4.7	4.5	9.2	1.36	0.4	73
	2.0	D	D	D	D	D	D
CaSO ₄	3.0	D	D	D	D	D	D
	5	5.3	10.4	15.6	0.56	1.1	114
	10	19.4	31.5	50.9	0.61	4.0	116
	25	29.6	34.8	64.3	0.89	3.2	92
	50	100.3	106.1	206.3	0.98	16.5	151
FGD-22	75	156.8	303.6	460.4	0.52	29.8	98
	5	270	427	697	0.65	39.5	94
	10	351	783	1134	0.45	51.0	63
	25	581	1034	1615	0.56	52.6	50
	50	578	784	1361	0.73	40.0	54
FGD-27	75	520	598	1119	0.90	36.7	59
	1.0	248	437	684	0.63	50.4	114
	2.5	354	766	1120	0.47	46.9	61
	5.0	393	822	1215	0.49	42.9	53
	10	378	707	1035	0.54	30.2	42
FGD-28	25	76	79	155	1.00	6.8	83
	0.25	12.0	12.7	24.7	1.04	1.9	145
	0.5	23.2	26.7	49.9	0.80	3.7	132
	1.0	44.8	54.6	99.4	0.96	8.2	145
	2.0	137.4	153.4	290.8	0.93	17.9	120
LSD	3.0	132.2	111.1	243.3	1.36	11.4	111
		14.1	20.6	32.3	0.06	1.8	5
(P < 0.05)							

D = Dead plants

Table 4. White clover shoot, root, and total dry matter (DM), shoot/root (S/R) DM ratio, total and specific root lengths (RL), and number of root nodules for when grown in acidic soil amended with various levels of CaCO₃, CaSO₃, CaSO₄, and three FGDs.

Treatment	Level (% in soil)	Plant dry matter (mg plant ⁻¹)				Root length (RL) and nodulation			
		Shoots	Roots	Total	S/R DM ratio	Total RL (m plant ⁻¹)	Specific RL (m g ⁻¹ DM)	Nodules (No. plant ⁻¹)	
Control CaCO ₃	0	84	76	159	1.12	14.9	198	0	
	0.125	1126	741	1867	1.52	138.2	187	22	
	0.25	1277	870	2147	1.55	136.4	160	140	
CaSO ₃	0.5	1585	762	2348	2.07	100.9	134	386	
	0.25	45	23	68	1.98	5.6	252	0	
	0.5	11	3	14	2.85	0.6	285	0	
CaSO ₄	1.0	D	D	D	D	D	D	D	
	2.0	D	D	D	D	D	D	D	
	3.0	D	D	D	D	D	D	D	
FGD-22	5	39	24	63	1.60	2.8	114	0	
	10	34	19	53	1.86	1.4	79	0	
	25	291	107	398	2.84	12.1	142	1	
FGD-22	50	161	133	294	1.35	21.1	152	0	
	75	425	257	682	1.70	42.6	168	15	
	5	609	402	1010	1.52	72.4	178	2	
FGD-22	10	1185	696	1882	1.75	106.4	157	110	
	25	1255	664	1920	1.92	100.1	151	365	
	50	820	459	1280	1.81	76.8	166	457	

(continued)

Table 4. Continued.

Treatment	Level (% in soil)	Plant dry matter (mg plant ⁻¹)				Root length (RL) and nodulation		
		Shoots	Roots	Total	S/R DM ratio	Total RL (m plant ⁻¹)	Specific RL (mg ⁻¹ DM)	Nodules (No. plant ⁻¹)
FGD-27	75	1049	500	1549	2.15	65.2	135	452
	1.0	608	504	1112	1.20	87.2	172	0
	2.5	955	1129	2083	1.19	118.7	138	134
	5.0	917	687	1603	1.38	95.1	138	314
	10	780	455	1235	1.73	56.8	127	203
FGD-28	25	15	13	28	1.24	2.6	207	0
	0.25	313	201	514	1.55	35.8	181	0
	0.5	535	338	874	1.75	57.1	177	0
	1.0	504	322	826	1.59	61.9	191	0
	2.0	560	288	848	1.98	56.9	203	3
LSD (P < 0.05)	3.0	589	240	829	2.50	42.9	178	15
		42	41	67	0.12	3.4	10	

D = dead plants.

in soil receiving the various amendments. With only few exceptions, alfalfa root DM was greater than shoot DM when plants were grown with the various levels of control compounds and FGDs (Table 3), while shoot DM was greater than root DM for white clover (Table 4). Thus, shoot/root DM ratios for alfalfa were lower (mostly < 1.0) compared to white clover (> 1.0) (Tables 3 and 4). The most effective amendments for enhancing legume growth at the lowest levels added to soil were CaCO_3 , FGD-22, and FGD-27. Increases in total DM at the lowest levels of added amendment over unamended soil were between 74- and 84-fold for alfalfa and only 10- to 13-fold for white clover. The DM of each legume continued to increase as level of CaCO_3 , FGD-22, and FGD-27 increased in soil, and were maximum at 25% FGD-22 and 5.0% FGD-27 for alfalfa and 2.5% FGD-27 for white clover before DM decreased. Of the amendments tested, plants grown with CaCO_3 , FGD-22, and FGD-27 had highest DM. Both alfalfa and white clover grown in soil amended with CaSO_3 grew poorly and plants died as CaSO_3 levels increased. Alfalfa and white clover grown in soil amended with CaSO_4 and FGD-28 had relatively low total DM at the lowest levels added. As level of these amendments increased, DM of alfalfa increased consistently, while white clover remained relatively constant. Maximum DM for plants grown with CaSO_4 and FGD-28 were consistently lower than for plants grown with CaCO_3 , FGD-22, and FGD-27.

Total RL of both legumes followed trends similar to root DM, and both species had relatively high RL values (Tables 3 and 4). Overall SRL values for alfalfa were lowest in soil amended with FGD-22, FGD-27, and the highest level of CaCO_3 compared to the other amendments (Table 3), while SRL values for white clover remained relatively constant over the various levels of amendment added (Table 4). Specific RL values for alfalfa grown with CaSO_4 and FGD-28 were relatively similar to or only slightly higher than for plants grown in unamended soil. CaCO_3 , FGD-22, and FGD-27 were effective in enhancing nodule formation on roots of white clover, while CaSO_3 , CaSO_4 , and FGD-28 were ineffective (Table 4).

Cool-Season Grasses

The orchardgrass cultivar grew considerably better in unamended soil than the tall fescue cultivar, but differences between plant DM increases with low levels of added amendment were considerably greater for tall fescue than for orchardgrass (Tables 5 and 6). Root DM was consistently higher for both of these cool-season grasses than shoot DM, and shoot/root DM ratios were generally lower for tall fescue than for orchardgrass (Tables 5 and 6). Both of these plant species had good growth when soil was amended with CaCO_3 ,

Table 5. Orchardgrass shoot, root, and total dry matter (DM), shoot/root (S/R) DM ratio, and total and specific root lengths when grown in acidic soil amended with various levels of CaCO_3 , CaSO_3 , CaSO_4 , and three FGDs.

Treatment	Level (% in soil)	Plant dry matter (mg plant ⁻¹)			S/R DM ratio	Root length	
		Shoots	Roots	Total		Total (m plant ⁻¹)	Specific (m g ⁻¹ DM)
Control	0	273	58	331	7.09	25	866
CaCO ₃	0.125	757	653	1409	1.19	146	232
	0.25	1048	1648	2696	0.65	371	226
	0.5	810	2586	3396	0.44	362	141
CaSO ₃	0.25	68	19	87	5.55	4	248
	0.5	99	30	375	8.15	4	200
	1.0	143	125	268	6.12	16	223
CaSO ₄	2.0	133	167	300	10.35	< 1	123
	3.0	261	109	370	6.03	28	276
	5	272	59	331	4.83	19	313
	10	548	875	1423	1.98	115	191
	25	839	849	1688	1.05	166	209
	50	971	1648	2618	0.64	258	170
	75	1177	2014	3191	0.67	231	123
FGD-22	5	1104	2775	3879	0.45	335	140
	10	1139	1879	3018	0.64	296	159
	25	974	3310	4283	0.40	395	148
	50	511	1592	2103	0.34	242	158
	75	336	856	1192	0.43	178	221
FGD-27	1.0	1236	3279	4515	0.45	303	102
	2.5	1321	3481	4801	0.41	372	112
	5.0	1566	2501	1067	0.71	361	158
	10	1482	1657	3139	0.93	255	156
	25	965	796	1761	1.23	113	146
FGD-28	0.25	1153	3570	4723	0.33	328	93
	0.5	1092	2334	3426	0.55	311	145
	1.0	1246	2694	3939	0.52	312	126
	2.0	1236	2534	3770	0.51	326	132
	3.0	1203	2193	3395	0.56	286	136
LSD		28	167	174	0.61	31	43
(P < 0.05)							

Table 6. Tall fescue shoot, root, and total dry matter (DM), shoot/root (S/R) DM ratio, and total and specific root lengths when grown in acidic soil amended with various levels of CaCO_3 , CaSO_3 , CaSO_4 , and three FGDs.

Treatment	Level (% in soil)	Plant dry matter (mg plant ⁻¹)				Root length	
		Shoots	Roots	Total	S/R	Total (m plant ⁻¹)	Specific (m g ⁻¹ DM)
					DM ratio		
Control	0	29	5	33	0.63	2	311
CaCO ₃	0.125	1373	4523	5896	0.31	522	113
	0.25	1576	6909	8486	0.27	393	60
	0.5	1627	5247	6874	0.33	497	100
CaSO ₃	0.25	10	3	13	3.20	<1	147
	0.5	5	1	6	4.87	<1	123
	1.0	5	2	7	2.68	<1	64
	2.0	4	1	6	3.55	<1	60
	3.0	40	6	46	6.99	2	257
	5	11	2	14	5.05	<1	240
CaSO ₄	10	43	9	52	4.78	2	298
	25	278	82	360	5.30	15	250
	50	1106	3083	4190	0.48	320	109
FGD-22	75	1228	9788	11770	0.12	567	54
	5	1140	5156	6295	0.25	398	81
	10	1230	8942	10170	0.14	572	64
	25	1082	7225	8307	0.22	527	111
	50	635	2364	2999	0.30	360	163
	75	352	1348	1700	0.28	273	202
FGD-27	1.0	1488	2567	4055	0.65	301	136
	2.5	1319	2334	3653	0.57	355	151
	5.0	1352	2295	3647	0.60	409	177
	10	1658	2477	4135	0.73	264	114
	25	1086	1032	2118	1.20	148	140
FGD-28	0.25	1184	1203	2387	1.00	226	192
	0.5	1335	2234	3569	0.62	322	150
	1.0	1301	2700	4001	0.51	383	147
	2.0	1626	3218	4844	0.60	420	149
	3.0	1451	2943	4394	0.57	355	128
LSD (P < 0.05)		27	267	286	0.48	14	12

CaSO₄, and the FGDs. Highest orchardgrass DM was obtained when plants were grown with 0.5% CaCO₃, 75% CaSO₄, 25% FGD-22, 2.5% FGD-27, and 0.25% FGD-28 (Table 5), and highest tall fescue DM was obtained when plants were grown with 0.25% CaCO₃, 75% CaSO₄, 10% FGD-22, 10% FGD-27, and 2.0% FGD-28 (Table 6). Orchardgrass grew fairly well with additions of CaSO₃, but tall fescue did not. Both of these cool-season grasses had consistent increases in DM as level of CaSO₄ increased, but the response of tall fescue was more dramatic than orchardgrass (> 350-fold for tall fescue compared to 10-fold for orchardgrass between 5 and 75% of added CaSO₄). The DM of orchardgrass and tall fescue grown with the lowest level of CaSO₄ (5%) was no higher and even below that of plants grown in unamended soil before increasing extensively as level of CaSO₄ increased. In the case of tall fescue, increases in DM did not resume until CaSO₄ level was above 10%. Except for plants grown with CaSO₃, both orchardgrass and tall fescue had extensive RL in amended soil (Tables 5 and 6). Both species grown with the amendments had lower SRL values than plants grown in unamended soil (Tables 5 and 6). Orchardgrass generally had lower SRL values when grown with FGDs than with CaCO₃, CaSO₄, and CaSO₃, while tall fescue had lower SRL values when grown with CaCO₃, CaSO₃, and each of the FGDs compared to CaSO₄.

Warm-Season Grasses

Both warm-season grasses grew well in unamended soil, and DM yields with added amendments were only 2- to 3-fold magnitude higher than those of plants grown in unamended soil (Tables 7 and 8). Shoot DM was higher than root DM for each of these species, and shoot/root DM ratios of eastern gamagrass were generally higher than those for switchgrass (Tables 7 and 8). Added CaCO₃ improved growth of these plant species by only ~2-fold, with switchgrass having slightly more positive responses than eastern gamagrass. The lower levels of CaSO₃ had no or relatively minor negative effects on DM of both switchgrass and eastern gamagrass, but plants grew very little or were dead at the highest levels of CaSO₃. Both species had DM increases from added FGDs at the lower levels, but decreased at the higher levels. Eastern gamagrass grown with 5 and 10% CaSO₄ levels had lower DM than plants grown in unamended soil before increasing at the highest CaSO₄ levels (Table 8), and switchgrass had DM increases when plants were grown with all levels of CaSO₄ (Table 7). Total RL was relatively good for these warm-season grasses grown with the various amendments added, except CaSO₃ (Tables 7 and 8). Specific RL values of switchgrass were generally lower for plants

Table 7. Switchgrass shoot, root, and total dry matter (DM), shoot/root (S/R) DM ratio, and total and specific root lengths when grown in acidic soil amended with various levels of CaCO_3 , CaSO_3 , CaSO_4 , and three FGDs.

Treatment	Level (% in soil)	Plant dry matter (mg plant ⁻¹)				Root length	
		Shoots	Roots	Total	S/R	Total (m plant ⁻¹)	Specific (m g ⁻¹ DM)
					DM ratio		
Control	0	659	220	879	5.44	25.1	143
CaCO ₃	0.125	921	719	1640	1.30	77.2	105
	0.25	1160	894	2054	1.33	80.1	88
	0.5	1023	896	1919	1.18	60.3	65
CaSO ₃	0.25	713	338	1051	2.34	37.4	90
	0.5	213	116	329	3.90	6.1	108
	1.0	148	68	215	2.18	4.6	92
	2.0	64	2	66	32.25	0.4	100
	3.0	11	2	13	5.50	0.2	180
CaSO ₄	5	1202	674	1875	1.88	64.9	97
	10	1111	723	1834	1.64	71.9	98
	25	1576	838	2413	2.02	72.7	85
	50	995	461	1456	2.26	37.9	88
	75	944	433	1377	2.41	36.8	88
FGD-22	5	1346	1238	2584	1.14	81.0	65
	10	1568	1304	2872	1.26	104.7	78
	25	1486	1187	2673	1.30	93.8	78
	50	701	400	1100	1.80	50.3	122
	75	431	290	721	1.58	30.8	117
FGD-27	1.0	1071	983	2054	1.09	92.7	93
	2.5	1352	873	2224	1.58	85.1	98
	5.0	1303	722	2025	1.81	65.7	90
	10	910	450	1360	2.07	36.8	83
	25	14	14	28	1.03	1.1	82
FGD-28	0.25	959	657	1616	1.55	73.0	115
	0.5	1054	778	1832	1.46	74.5	97
	1.0	1314	868	2182	1.59	92.0	105
	2.0	1111	737	1848	1.52	65.1	90
	3.0	912	420	1332	2.23	37.1	90
LSD (P < 0.05)		32	30	54	0.56	28.3	11

Table 8. Eastern gamagrass shoot, root, and total dry matter (DM), shoot/root (S/R) DM ratio, and total and specific root lengths when grown in acidic soil amended with various levels of CaCO_3 , CaSO_3 , CaSO_4 , and three FGDs.

Treatment	Level (% in soil)	Plant dry matter (mg plant ⁻¹)				Root length	
		Shoots	Roots	Total	S/R DM ratio	Total (m plant ⁻¹)	Specific (m g ⁻¹ DM)
Control	0	577	247	824	2.36	18.0	74
CaCO ₃	0.125	946	564	1510	1.70	43.4	78
	0.25	845	611	1456	1.44	41.5	68
CaSO ₃	0.5	586	387	972	1.52	29.4	75
	0.25	600	229	828	2.78	16.1	70
	0.5	679	228	907	5.89	19.3	152
	1.0	252	55	306	4.58	3.3	49
CaSO ₄	2.0	D	D	D	D	D	D
	3.0	D	D	D	D	D	D
	5	369	129	498	3.10	7.7	59
	10	411	153	564	2.58	8.7	58
	25	642	214	856	2.94	12.8	63
	50	1176	377	1553	3.24	24.9	68
	75	1331	408	1738	3.34	31.3	76
FGD-22	5	1099	646	1746	1.70	54.7	85
	10	1374	492	1866	2.79	60.3	74
	25	351	458	810	2.56	6.7	67
	50	215	85	300	1.69	5.7	34
	75	293	99	392	3.45	5.7	55
FGD-27	1.0	972	498	1470	1.97	40.2	83
	2.5	802	456	1258	1.90	36.3	77
	5.0	700	388	1087	1.84	25.7	66
	10	364	148	512	2.54	9.3	62
	25	91	26	117	3.43	1.0	40
FGD-28	0.25	667	388	1045	1.77	33.1	88
	0.5	996	594	1590	1.68	52.9	89
	1.0	1294	706	2001	1.83	58.8	82
	2.0	1225	692	1917	1.77	58.6	84
	3.0	602	295	896	2.12	27.9	95
LSD		55	38	83	1.32	2.6	7
(P < 0.05)							

D = dead plants.

grown in amended compared to unamended soil (Table 7), while amendments had relatively little effect on SRL values of eastern gamagrass, except at the highest levels of FGD-22 and FGD-27 where they were lower (Table 8).

DISCUSSION

Increased soil pH_{Ca} was expected from CaCO_3 (lime), and only limited increases in soil pH_{Ca} were expected from added CaSO_3 and CaSO_4 as both of these chemically pure compounds should have had no CaCO_3 equivalency (CCE). Increases in soil pH_{Ca} from the added FGDs indicated that these products contained some alkaline substance(s), which is consistent with CCE values measured in these products (Table 1). FGD-28 with its relatively high CCE (69%) increased soil pH_{Ca} consistently, even at low levels. FGD-27, even with its relatively low CCE (13%), increased soil pH_{Ca} to fairly high values at its highest level added to soil (25%).

Chemical grade CaCO_3 contained few soluble salts and/or did not increase availability of other salts once added to soil, thus this compound had little effect on soil EC. CaSO_4 might be expected to increase soil EC to some extent, since this salt has some, although relatively low, solubility.^[23] However, CaSO_4 would not be expected to increase soil EC beyond the level at which the soil solution would become saturated ($\sim 0.07\%$) due to its solubility limit. Changes in EC from added CaSO_3 might be expected to be similar to that of CaSO_4 , since CaSO_3 is readily oxidized to CaSO_4 .^[24] Nevertheless, EC increases from added CaSO_3 above that of CaSO_4 occurred in soil where the various plant species, except orchardgrass, were grown. Relatively high soil EC from added CaSO_3 may have been because of HSO_3^- formation in acidic soil, as this ion should be prominent in solution at low soil pH with added CaSO_3 .^[25] The increase in EC with added FGD-27 may have been due to formation of $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$.^[21]

Only FGD-27 at its highest level increased soil pH_{Ca} and EC sufficiently to potentially induce detrimental effects to plants. Soil at pH 7 to 8 may induce deficiencies of P, Fe, Zn, and/or Mn because solubilities of these minerals are reduced as soil pH increases.^[26] Except for added CaSO_3 , EC values resulting from added FGDs were generally not sufficiently high to detrimentally affect growth of most plants. Soil EC values reported to decrease growth of salt sensitive, moderately salt sensitive, and moderately salt tolerant plants have been 1.5, 3.5, and 6.5 dS m^{-1} , respectively.^[27] Decreases in plant growth from added CaSO_3 likely occurred because of S-SO_3 toxicity rather than from high EC, as S-SO_3 even at low levels is known to be harmful to many plants.^[28] Increases in soil pH_{Ca} and EC from the FGDs were likely because of alkalizing

agents and soluble salts included in the products for stabilization. Both FGD-27 and FGD-28 had relatively high Mg (Table 1), and Mg salts are usually more soluble than Ca salts. In addition, Mg in FGD-27 came from $\text{Mg}(\text{OH})_2$ (a basic compound that can raise soil pH), and the high Ca and Mg in FGD-28 (Table 1) may have come from additional Ca–Mg incorporated into the product for stabilization [Ca–MgO , $\text{Ca–Mg}(\text{OH})_2$, and/or Ca–MgCO_3]. Even though it is not known what compounds were added to FGD-28, this product had 69% CCE and 509 Ca and 24 Mg in mg kg^{-1} product (Table 1). FGD-22 apparently had some added ingredients to increase soil pH and provide positive responses to plants at low levels. Plant growth responses from added FGD-22 were also quite different from those of chemical grade CaSO_4 .

The six forage species, as expected, had greater DM when grown with added CaCO_3 compared to unamended soil, but the legumes and tall fescue responded more to added CaCO_3 than orchardgrass and the warm-season grasses. Legumes are known to need relatively higher soil pH for optimal growth compared to grasses.^[29,30] Regardless of plant species, roots had greater positive effects from added CaCO_3 than shoots. The unamended soil with pH_{Ca} 3.9 was detrimental to root growth, which was likely because of Al (and possibly Mn) toxicity. Aluminum toxicity often restricts root length and diminishes acquisition of essential mineral nutrients.^[31] Since this batch of unamended soil had high Al (88% saturation) and low P (3.1 mg kg^{-1} soil), mineral nutrient toxicities and/or deficiencies would be expected. Phosphorus and Mg deficiencies were common on many plants grown in this and other low pH soils (R.B. Clark, personal observations). Reduced DM for grasses grown at the highest level of CaCO_3 added may have occurred because of “overliming” stress effects sometimes associated with induced P, Mg, and/or other mineral deficiencies.^[32,33] Similar reductions in DM were noted for grasses in some of the early experiments in this series where CaCO_3 was added up to 1% (R.B. Clark, unpublished data), and for maize grown in an acidic soil amended with CaCO_3 at levels similar to those used in these experiments.^[34]

Except for orchardgrass, switchgrass, and eastern gamagrass, plants grown with CaSO_3 even at low levels did not grow well and were usually dead when grown with the highest levels. S–SO_3 even at low levels is normally harmful to plants,^[15,24,28,34] and caution is needed if plants are to be grown in soil amended with FGDs containing S–SO_3 . Since S–SO_3 is oxidized to S–SO_4 within relatively short time periods (days or weeks)^[24,35] and if sufficient exposure to oxygen/air and time are provided, soils receiving added CaSO_3 should provide effects similar to those of CaSO_4 once S–SO_3 has been oxidized to S–SO_4 . Nevertheless, high soil pH and high soil moisture (lack of O_2) can prolong time needed to convert S–SO_3 to S–SO_4 .^[35] In addition,

CaSO_3 can release SO_2 gas under acidic conditions,^[25] which is toxic to plants.^[24]

CaSO_4 had to be added at relatively high levels before enhancement effects on DM occurred, and DM of plants grown in soil with 5–10% CaSO_4 sometimes had lower DM than plants grown in unamended soil. These reductions in DM with low levels of CaSO_4 might be attributed to induced Al toxicity to roots from Ca^{2+} displacement of Al^{3+} on soil exchange sites,^[15] although induced Mg deficiency from imbalanced Ca:Mg ratios^[36] should not be ruled out. Once CaSO_4 was added at higher levels to overcome detrimental effects in the soil, growth improved likely because of Al inactivation (e.g., formation of non-toxic Ca–Al and/or S–Al compounds) and because of increases in soil pH to values where Al would be inactivated ($\text{pH}_{\text{Ca}} \sim 5.5$).^[15,34] Except for switchgrass, even the highest level of CaSO_4 used in these experiments (75% in soil mixes) was not detrimental to plant growth.

Added FGDs improved growth of the plants used in these studies. FGD-27 and FGD-28 generally provided the best growth at the lowest levels added to soil. Many FGDs contain minerals added during generation and/or curing (stabilization) that provide enhancement effects to plants. Although many mineral disorders occur on plants grown in acidic soil, Mg deficiency and Al toxicity are commonly reported.^[37] The FGDs used in our studies appeared to contain added substances that enhanced growth, so that DM was equal to or greater than those obtained with chemical grade CaCO_3 and CaSO_4 , which are major components of FGDs. Both FGD-27 and FGD-28 contained relatively high Mg and raised soil pH extensively, and these FGDs could have alleviated Mg deficiency and Al toxicity that might have otherwise been imposed on plants grown in this acidic soil. Even though FGD-22 functioned somewhat similar to pure CaSO_4 , this product appeared to contain added substances that enhanced growth. FGD-27 and FGD-28 also appeared to have properties that were detrimental to plant growth when added at high levels, especially FGD-27. The detrimental effect of FGD-27 on DM at the highest levels added could have been caused by high B in the product (Table 1)^[38] and high soil pH disorders.

Plant species differed in response to each of the FGDs added to this acidic soil. Legumes and cool-season grasses received the greatest enhancement of growth from added FGDs, while enhanced growth of warm-season grasses was relatively small. Many warm-season grasses are considered to be relatively tolerant to soil acidity.^[29,30] Differences in responses among maize, soybean, cotton, and radish were reported when these plants were grown in acidic soil ($\text{pH}_{\text{Ca}} 4.9$) amended with various levels of a FGD in the field.^[19] Plants grown in our study had larger differences for root compared to shoot mass, and this was reflected in differences in shoot/root DM ratios. Alfalfa,

orchardgrass, and tall fescue had higher root than shoot DM and white clover, switchgrass, and eastern gamagrass had higher shoot than root DM.

Even though total RL changes were similar to root DM changes, SRL values (measure of root fineness) were generally lower for plants grown with added CaCO_3 , CaSO_4 , and FGDs than with CaSO_3 and in unamended soil. Plants grown under relatively good growing conditions generally have larger root diameters (lower SRL values) compared to smaller root diameters (higher SRL values) for plants grown under low nutrient conditions.^[39] Changes in root diameters might be explained in terms of mineral mobility and of soil volumes roots need to exploit, as evidenced by coarse roots being typical of nutrient-rich soils.^[39] In addition, Ca and K deficient roots were generally shorter and denser and had reduced root mass and length than roots adequately supplied with these minerals.^[40] The higher soil pH from added CaCO_3 , FGD-22, and FGD-27 enhanced white clover root ability to form nodules, which should enhance N_2 fixation and improve nutrition of legumes. Even with the fairly good growth that plants made when grown with FGD-28 and high CaSO_4 , nodules did not readily form on roots of these plants.

The FGDs used in our study benefited growth of forage plants grown in acidic soil, indicating that FGDs could be used effectively for growth enhancement of many plants. Concern might occur when using FGD gypsums at low levels, which may induce Al toxicity and/or Mg deficiency, as well as using too high levels of stabilized and FGD gypsums containing added substances like $\text{Mg}(\text{OH})_2$ and B, which could raise soil pH to excessive values and/or induce B toxicity. In addition, FGDs containing S- SO_3 should not be used until S- SO_3 has been converted to S- SO_4 .

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REFERENCES

1. ACAA, *Coal Combustion Product (CCP) Production and Use (Surveys)*; American Coal Ash Association: Alexandria, VA, 1999.

2. Alcordo, I.S.; Rechcigl, J.E. Phosphogypsum and other by-product gypsums. In *Soil Amendments and Environmental Quality*; Rechcigl, J.E., Ed.; Lewis Publ.: Boca Raton, FL, 1995; 365–425.
3. Bilski, J.J.; Alva, A.K.; Sajwan, K.S. Fly ash. In *Soil Amendments and Environmental Quality*; Rechcigl, J.E., Ed.; Lewis Publ.: Boca Raton, FL, 1995; 327–363.
4. Carlson, C.L.; Adriano, D.C. Environmental impacts of coal combustion residues. *J. Environ. Qual.* **1993**, 22, 227–247.
5. Korcak, R.F. Utilization of coal combustion by-products in agriculture and horticulture. In *Agricultural Utilization of Urban and Industrial By-products*; Karlen, D.L., Wright, R.J., Kemper, W.D., Eds.; Spec. Publ. No. 58; Am. Soc. Agron.: Madison, WI, 1995; 107–130.
6. Korcak, R.F. Agricultural uses of coal combustion byproducts. In *Agricultural Uses of Municipal, Animal, and Industrial Byproducts*; Wright, R.J., Kemper, W.D., Millner, P.D., Power, J.F., Korcak, R.F., Eds.; Cons. Res. Rep. No. 44; U.S. Dept. Agric., Agric. Res. Serv.: Beltsville, MD, 1998; 103–119.
7. Logan, T.J.; Burnham, J.C. The alkaline stabilization with accelerated drying process (N-Viro): an advanced technology to convert sewage sludge into a soil product. In *Agricultural Utilization of Urban and Industrial By-products*; Karlen, D.L., Wright, R.J., Kemper, W.D., Eds.; Spec. Publ. No. 58; Am. Soc. Agron.: Madison, WI, 1995; 209–223.
8. Miller, W.P.; Sumner, M.E. Agricultural and industrial uses of byproduct gypsums. In *Agricultural Uses of Byproducts and Wastes*; Rechcigl, J.E., MacKinnon, H.C., Eds.; Am. Chem. Soc.: Washington, DC, 1997; 226–239.
9. Norton, D.; Shainberg, I.; Cihacek, L.; Edwards, J.H. Erosion and soil chemical properties. In *Soil Quality and Soil Erosion*; Lal, R., Ed.; CRC Press: Boca Raton, FL, 1999; 39–56.
10. Ritchey, K.D.; Elrashidi, M.A.; Clark, R.B.; Baligar, V.C. Potential for utilizing coal combustion residues in co-utilization products. In *Beneficial Co-utilization of Agricultural, Municipal and Industrial By-products*; Brown, S., Angle, J.S., Jacobs, L., Eds.; Kluwer Acad. Publ.: New York, 1998; 139–147.
11. Shainberg, I.; Sumner, M.E.; Miller, W.P.; Farina, M.P.W.; Pavan, M.A.; Fey, M.V. Use of gypsum on soils: a review. *Adv. Soil Sci.* **1989**, 9, 1–111.
12. Sharpley, A.N.; Daniel, T.; Sims, T.; Lemunyon, J.; Stevens, R.; Parry, R. *Agricultural Phosphorus and Eutrophication*; U.S. Dept. Agric., Agric. Res. Serv.: Washington, DC, 1999; ARS–149.

13. Stout, W.L.; Sharpley, A.N.; Pionke, H.B. Reducing soil phosphorus solubility with coal combustion by-products. *J. Environ. Qual.* **1998**, *27*, 111–118.
14. Clark, R.B.; Zeto, S.K.; Ritchey, K.D.; Wendell, R.R.; Baligar, V.C. Coal combustion by-product use on acid soil: effects on maize growth and soil pH and electrical conductivity. In *Agricultural Utilization of Urban and Industrial By-products*; Karlen, D.L., Wright, R.J., Kemper, W.D., Eds.; Spec. Publ. No. 58; Am. Soc. Agron.: Madison, WI, 1995; 131–155.
15. Clark, R.B.; Zeto, S.K.; Ritchey, K.D.; Wendell, R.R.; Baligar, V.C. Effects of coal flue; gas desulfurization combustion by-products and calciumsulfite, nsulfate, and ncarbonate on maize grown in acid soil. In *Plant-Soil Interactions at Low pH: Principles and Management*; Date, R.A., Grundon, N.J., Rayment, G.E., Probert, M.E., Eds.; Kluwer Acad. Publ.: New York, 1995; 519–525.
16. Dorsett, D.J.; Nickel, L.; Pennington, H.D.; Calloway, D. Preliminary evaluation of coal generated by-product gypsum as a soil amendment on improved hybrid bermudagrass. *Proceedings of 11th Int. Symp. on Use and Management of Coal Combustion Products (CCPs)*; Electric Power Res. Inst.: Palo Alto, CA, 1995; Vol. 1, 10-1–10-7.
17. Stout, W.L.; Priddy, W.E. Use of flue gas desulfurization (FGD) by-product gypsum on alfalfa. *Commun. Soil Sci. Plant Anal.* **1996**, *27*, 2419–2432.
18. Alva, A.K.; Zhu, B.; Hostler, H.K.; Obreza, T.A. Citrus tree growth and fruit production response to flue-gas desulfurization gypsum amendment in sandy soils. In *Biogeochemistry of Trace Elements in Coal and Coal Combustion Byproducts*; Sajwan, K.S., Alva, A.K., Keefer, R.F., Eds.; Kluwer Academic/Plenum Publ.: New York, 1999; 293–307.
19. Punshon, T.; Knox, A.S.; Adriano, D.C.; Seaman, J.C.; Weber, J.T. Flue gas desulfurization (FGD) residue: potential applications and environmental issues. In *Biogeochemistry of Trace Elements in Coal and Coal Combustion Byproducts*; Sajwan, K.S., Alva, A.K., Keefer, R.F., Eds.; Kluwer Acad./Plenum Publ.: New York, 1999; 7–28.
20. Stehouwer, R.C.; Sutton, P.; Dick, W.A. Transport and plant uptake of soil-applied dry flue gas desulfurization by-products. *Soil Sci.* **1996**, *161*, 562–574.
21. Stehouwer, R.C.; Dick, W.A.; Sutton, P. Acidic soil amendment with a magnesium-containing fluidized bed combustion by-product. *Agron. J.* **1999**, *91*, 24–32.
22. Snedecor, G.R.; Cochran, W.G. *Statistical Methods*; Iowa College Press: Ames, IA, 1957.

23. Weast, R.C., Ed. *CRC Handbook of Chemistry and Physics*; CRC Press: Boca Raton, FL, 1978; B-105.
24. Ritchey, K.D.; Kinraide, T.B.; Wendell, R.R. Interactions of calcium sulfite with soils and plants. *Plant Soil* **1995**, *173*, 329–335.
25. Wedzicha, B.L. *Chemistry of Sulfur Dioxide in Foods*; Elsevier Appl. Sci. Publ.: Amsterdam, 1984.
26. Marschner, H. *Mineral Nutrition of Higher Plants*; Academic Press: San Diego, CA, 1995.
27. Maas, E.V. Crop salt tolerance. In *Agricultural Salinity Assessment and Management*; Tanji, K.K., Ed.; Manuals and Reports on Engineering Practice No. 71; Am. Soc. Civil Engin.: New York, 1990; 262–304.
28. Bertelsen, F.; Gissel-Nielsen, G. Toxicity of root-applied sulphite in *Zea mays*. *Environ. Geochem. Health* **1987**, *9*, 12–16.
29. Barnes, R.F.; Miller, D.A.; Nelson, C.J., Eds. *Forages: An Introduction to Grassland Agriculture*; Iowa State Univ. Press: Ames, IA, 1995; Vol. 1.
30. Heath, M.E.; Metcalfe, D.S.; Barnes, R.F., Eds. *Forages: The Science of Grassland Agriculture*, 3rd Ed.; Iowa State Univ. Press: Ames, IA, 1973.
31. Foy, C.D. Soil chemical factors limiting plant root growth. *Adv. Soil Sci.* **1992**, *19*, 87–149.
32. Grove, J.H.; Sumner, M.E. Lime induced magnesium stress in corn: impact on magnesium and phosphorus availability. *Soil Sci. Soc. Am. J.* **1985**, *49*, 1192–1196.
33. Sumner, M.E.; Farina, M.P.W.; Hurst, V.J. Magnesium fixation: a possible cause of negative yield responses to lime applications. *Commun. Soil Sci. Plant Anal.* **1978**, *9*, 995–1007.
34. Clark, R.B.; Zeto, S.K.; Ritchey, K.D.; Baligar, V.C. Mineral acquisition by maize grown in acidic soil amended with coal combustion products. *Commun. Soil Sci. Plant Anal.* **2001**, *32*, 1861–1884.
35. Bertelsen, F.; Gissel-Nielsen, G. Oxidation of sulphite originating from flue gas desulfurization waste in soil. *Environ. Geochem. Health* **1988**, *10*, 26–30.
36. Clark, R.B.; Zeto, S.K.; Ritchey, K.D.; Baligar, V.C. Maize growth and mineral acquisition on acid soil amended with flue gas desulfurization by-products and magnesium. *Commun. Soil Sci. Plant Anal.* **1997**, *28*, 1441–1459.
37. Clark, R.B.; Baligar, V.C. Acidic and alkaline soil constraints on plant mineral nutrition. In *Plant-Environment Interactions*, 2nd Ed.; Wilkinson, R.E., Ed.; Marcel Dekker, Inc.: New York, 2000; 133–177.

38. Clark, R.B.; Zeto, S.K.; Ritchey, K.D.; Baligar, V.C. Boron accumulation by maize grown in acidic soil amended with coal combustion products. *Fuel* **1999**, *78*, 179–185.
39. Fitter, A. Characteristics and functions of root systems. In *Plant Roots: The Hidden Half*, 2nd Ed.; Waisel, Y., Eshel, A., Kafkafi, U., Eds.; Marcel Dekker, Inc.: New York, 1996; 1–20.
40. Baligar, V.C.; Fageria, N.K.; Elrashidi, M.A. Toxicity and nutrient constraints on root growth. *HortScience* **1998**, *33*, 960–965.