INFLUENCE OF AMENDMENTS ON PHOSPHOGYPSUM CHEMICAL CHARACTERISTICS AND BERMUDAGRASS GROWTH[1]

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__Abstract:__ Phosphogypsum (PG) is primarily a calcium sulfate dihydrate ($CaSO_4.2H_2O$) byproduct of the production of phosphoric acid from phosphate ore. Approximately 5 mt of PG is produced per metric ton of phosphoric acid. Acidity and nutrient deficiencies are concerns that must be addressed for successful establishment of vegetation in PG. Therefore, a glasshouse study was conducted to determine the effects of dolomite, phosphatic clay (PC), and sewage sludge (SS) on PG chemical characteristics and bermudagrass (__Cynodon__ __dactylon__ [L.] Pers.) growth in PG. Phosphogypsum from an active stack, International Mineral Corp. (IMC-PG), and an old, inactive stack, Estech (ET-PG), was used. The pH and EC in water (2:1, V:W) were 2.78 and 4.16 dS/m for IMC-PG, and 4.82 and 2.29 dS/m for ET-PG. According to Mehlich-I extraction interpretations, both PG sources are classified as deficient in magnesium (Mg) and potassium (K) for optimum plant growth. Dolomite, ranging from 0.87 to 6.98 g/kg, PC from 21.7 to 174 g/kg, and SS from 4.35 to 17.4 g/kg were applied to IMC-PG. Similarly, dolomite at 0.22 to 1.74 g/kg, PC at 0.87 to 6.96 g/kg, and SS at 0.87 to 3.48 g/kg were applied to ET-PG. Each rate of amendment was increased successively by a factor of 2 to give 4 rates of dolomite and PC, respectively, and 3 rates of SS, and was mixed with the PG source and incubated for six months prior to this study. At the beginning of this study, ammonium nitrate (NH_4NO_3), potassium-magnesium sulfate (K_2SO_4-$MgSO_4$), and potassium sulfate (K_2SO_4) fertilizers were selectively added to supply 50 mg/kg N, 20 mg/kg K, and 12 mg/kg Mg before sowing (0.14 g seeds/pot). Germination and growth occurred at pH 4.3 despite moderate salinity (15.6 dS/m), suggesting that attaining a desired pH is more critical than salinity for germination and growth. Phosphatic clays reduced salinity in recently decommissioned stacks that are generally higher in salts. The rates of amendments applied to ET-PG did not supply sufficient K for plant growth. Additionally, SS rates did not supply sufficient Mg. Dolomite, PC, and SS each have potential for use as nutrient sources and for raising pH. However, bigher rates would be required to provide adequate nutrients in older, leached stacks and to increase pH in recently deactivated stacks.

Additional Key Words: dolomite, phosphatic clay, sewage sludge, acidity, electrical conductivity.

__Introduction__

Phosphogypsum (PG) is a solid byproduct of phosphoric acid production from phosphate rock. For each metric ton of phosphoric acid produced, there is a byproduct of approximately 5 mt PG. The PG is pumped as a slurry to an impoundment and allowed to settle. Small draglines are used to move some of the settled PG to raise the height of the dikes. This process results in an impoundment or "stack", which can grow up to a height of 60 m. Area of the stacks range from 20 ha to 200 ha; however, stacks currently occupy over 2,000 ha of land in Florida. Florida mining operations produce 33 million mt of PG annually (May and Sweeney 1980), with over 600 million mt already accumulated in stacks.

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Owing to the inherent low-level radioactivity present in PG, mostly from radium-226, the Environmental Protection Agency (EPA) has restricted PG use both for agricultural, and research and development purposes (Federal Register 1992). The EPA's main concern is with the emanation of radon-222 gas (a radioactive decay product of Ra-226) and possible increased concentrations of radon in dwellings built on PG treated sites. Most PG, therefore, remains in approximately 20 stacks throughout Florida. When PG stacks cease usefulness as deposition sites, they will have to be reclaimed in an environmentally acceptable manner. Establishing a vegetative cover will undoubtedly be part of any reclamation effort. Along with improving aesthetics, vegetative cover should reduce erosion, improve surface runoff quality, and promote PG stack use as a wildlife habitat.

Sparse natural vegetation on PG surfaces indicates that establishment of a vegetative cover is possible. Reasons for sparse vegetation on PG, based on preliminary PG analyses, include residual acidity and nutrient deficiencies or imbalances, along with low nutrient-holding capacity.

Phosphogypsum is comprised primarily of the moderately soluble neutral salt, $CaSO_4.2H_2O$, and as such should have minimal effect on soil acidity. However, residual phosphoric and sulfuric acids from the acidulation process, and secondary reaction products such as hydrofluoric and hydrofluorosilicic acids, render PG highly acidic (Smith and Wrench 1984). Acidity of different PG stacks in Florida commonly ranges from 2.1 to 3.8 (May and Sweeney 1980).

Studies have shown that bermudagrass can tolerate high acidity. Lundberg et al. (1977) reported bermudagrass growth under acidic conditions (pH 3.4). Similarly, growth of "Tifgreen" bermudagrass was observed at a pH of 3.5 by Sartain (1985). Therefore, bermudagrass establishment and growth on PG may be possible.

Phosphatic clay (PC) and sewage sludge (SS) may also have the potential to reduce PG acidity and supply nutrients. Application of limestone or dolomite is a common practice for reclaiming acidic mine spoils or processing wastes (Mays and Bengston 1978). Phosphatic clay, a byproduct washed from the phosphate ore during the beneficiation process, has a neutral to slightly alkaline pH, and may be used as a possible PG amendment for reducing acidity and as a plant-nutrient source. In reclaiming quartz sand-tailings, Mislevy and Blue (1981) reported higher yields using PC (pH = 7.8) with sand-tailings than when using sand-tailings alone due to nutrients and improved water-holding capacity.

Sewage sludge generally has a near-neutral pH (Jing and Logan 1992) and, therefore, should increase PG pH upon application. Cunningham et al. (1975) reported that N, P, and K released from SS application to a sandy loam soil increased yields of corn (Zea mays L.) and rye (Secale cereale L.). In reclaiming coal stripmines with either SS or chemical fertilizer, Seaker and Sopper (1988) reported that the rate of soil development and ecosystem recovery was enhanced on SS-amended sites when compared to fertilizer-amended sites.

The objective of this study was to determine the effects of selected quantities of dolomite, SS, and PC on the chemical characteristics of PG and on bermudagrass growth.

Materials and Methods

Very acidic PG from an active stack (IMC-PG) and less acidic PG from a stack that had been closed for more than 20 yr (ET-PG) were used. Partially consolidated PC was collected from a PC settling pond at the IMC Phosphoria mine. Anaerobically digested SS was collected from an advanced wastewater treatment plant (AWTP), near the City of Tampa, FL. The dolomite was agricultural-grade crushed dolomitic limestone, mined in central Florida.

Selected dolomite, PC, and SS rates were singly mixed with each PG source and incubated for 6 months prior to this study. Rates of dolomite mixed with IMC-PG ranged from 0.87 to 6.98 g/kg, PC from 21.7 to 174 g/kg, and SS from 4.35 to 17.4 g/kg. Similarly, dolomite at 0.22 to 1.74 g/kg, PC at 0.87 to 6.96 g/kg, and SS at 0.87 to 3.48 g/kg were mixed with ET-PG. The rates were increased successively by a factor of 2 to give 4 rates of dolomite and PC, respectively, and 3 rates of SS. Rates were selected to provide a range in pH.

Samples of raw and amended PG were analyzed for pH and electrical conductivity (EC) using a 2:1 volume to weight ratio (water:PG), and for various elements using Mehlich-I extractant according to Hanlon and DeVore (1989). According to Hanlon et al. (1993), the EC values (tables 2 and 3) were converted to estimated saturation extract EC (EC_e) as follows:

$$EC_e = (EC - 2.20) \times 8 + 2.20 \qquad (1)$$

where the factor 8 was obtained by taking the ratio of water content at EC measurement to that of the material at field capacity, which for this study was 26% by weight. The constant 2.20 is the EC of water saturated with gypsum (2.41 g/L). Dolomite was analyzed for HCl-extractable elements using Method M-110 of the Florida Department of Agriculture and Consumer Services Fertilizer Laboratory. Due to the high pH of PC, it was extracted instead with Mehlich-3 extractant (Mehlich 1984) using a procedure similar to that for the Mehlich-I extraction. Elemental analysis was accomplished using inductively coupled argon plasma spectrometry. Sewage sludge samples were dry-ashed and analyzed for total elemental concentrations. Analytical results for various elements in IMC-PG, ET-PG, dolomite, PC, and SS are shown in table 1, along with Kjeldahl-N content (Bremner and Mulvaney 1982) in SS, which was determined using an autoanalyzer.

Table 1. Concentrations of selected elements in the IMC-PG, ET-PG, dolomite, phosphatic clay, and sewage sludge samples used, mg/kg.[1]

Element	IMC-PG Mehlich-I extractable	ET-PG Mehlich-I extractable	Dolomite HCl extractable	Phosphatic clay Mehlich-III extractable	Sewage sludge Total conc. Dry ashing
N	ND	ND	ND	ND	59,000
P	1,904	106	190	74	14,237
K	55	1	140	245	807
Ca	4,008	4,234	208,833	ND	ND
Mg	76	3	104,666	1,967	2,114
Zn	2	0.4	7	3	902
Cu	1	0.3	6	2	428
Mn	4	0.1	31	5	67
Fe	51	5	1,155	100	11,605
Al	102	42	ND	250	4,904
B	ND	ND	ND	ND	34
Cd	ND	ND	ND	ND	16
Pb	ND	ND	ND	ND	154
Ni	ND	ND	ND	ND	41

[1]Mean of 5 replicates.
ND = Not Determined.

Two kilograms of air-dried material from previously incubated, amended-PG were transferred into a plastic pot (12 by 15 cm). The contents of each pot were moistened using de-ionized (DI) water to which fertilizer had been applied, as solutions, to the surface. Nitrogen as NH_4NO_3 was applied at 50 mg/kg to all pots not receiving SS. Similarly, K_2SO_4-$MgSO_4$ was applied to control units containing ET-PG to supply 20 mg/kg K and 12 mg/kg Mg, whereas K_2SO_4 was applied to dolomite-treated ET-PG to supply 20 mg/kg K. Common bermudagrass was used as a test species owing to its moderately high tolerance to salinity (Bernstein 1964), tolerance to low pH, and commercial seed availability, as well as its value as a livestock feed. Seeds were sown at a rate of 0.14 g seeds per pot. Bermudagrass aerial biomass was harvested after 10 weeks, oven-dried at 70° C, and the weight recorded. Biomass was digested using techniques similar to those for SS (dry ash), and analyzed for P, K, Mg, Zn, Mn, Cu, and Fe.

The single-factor experiment was arranged in a randomized complete block design, with four replicates. Analysis of variance, regression analyses, and single degree of freedom contrasts were used to determine significant differences within rates (Statistical Analysis System 1985). All of the analyses were conducted at the 0.05 level of probability.

Results and Discussion

Preplant Amended-Phosphogypsum Analyses

Analyses of Mehlich-I extractable elements from amended-PG prior to fertilization (tables 2 and 3) showed inadequate Mg and K concentration for optimum plant growth according to Kidder et al. (1990). Richardson (1992) also reported PG to be low in Mg and K. A comparison of the two PG sources indicates that ET-PG is consistently lower in extractable nutrient levels. This finding may be attributed to the stack having been deactivated for the past 20 yr. It thus has been subject to weathering and leaching for a greater period of time than the still-active IMC-PG stack. These differences persisted through the amendment treatments for the two PG sources as well. A linear increase in extractable Mg was observed by the addition of dolomite to both PG sources, though dolomite application to ET-PG actually decreased extractable P. Phosphatic clay applications increased extractable Mg, P, Mn, and Fe concentrations in both PG sources, and K concentration when applied to IMC-PG. Sewage sludge application increased extractable Zn, Cu, and Fe concentrations in both PG sources.

Influence of Electrical Conductivity and Acidity on Germination and Growth

Conversion of EC measurements made in a 2:1 (water:PG) ratio to estimated saturation extract EC (EC_e) values according to Hanlon et al. (1993) shows that the EC_e values for amended ET-PG ranged between 2.84 (EC = 2.28) and 3.56 (EC = 2.37 dS/m) (table 3). The protocol for EC conversion agreed well with actual EC_e measurements (Patel, unpublished data). Lower EC_e (essentially that of a saturated PG solution alone) along with a favorable pH (>4.3) contribute to germination and growth of bermudagrass in ET-PG. According to Hanlon et. al. (1993), the salinity effect threshold for bermudagrass is 6.9 dS/m, above which a yield decrease should be expected. Any 2:1 (V:W) EC in the tables in excess of 2.79 dS/m would exceed this threshold EC_e value. Low pH (<4.3) coupled with high EC_e (>6.9 dS/m) may have contributed to the lack of seed germination for several rates of SS and dolomite-amended IMC-PG. However, seed germination and growth at the highest dolomite and PC application rates for IMC-PG indicated that the influence of pH on seed germination and growth may be greater than that of EC. Dolomite and PC applications to ET-PG did not affect the EC, though SS produced a linear increase in EC ($EC = 2.28 + 2.59E\text{-}5(SS)$, $r^2 = 0.76$). For the IMC-PG, dolomite and SS applications did not affect EC, though PC application actually decreased EC compared to the unamended PG (table 2). Within PC rates, a linear increase in EC ($EC = 2.73 + 1.92E\text{-}6(PC)$, $r^2 = 0.48$) was observed. This indicates that PC is effective in reducing the influence of salinity on seed germination when reclaiming recently deactivated stacks.

Dolomite and SS rates produced linear responses in pH ($pH = 2.48 + 2.54E\text{-}4(Dolo)$, $r^2 = 0.93$ and $pH = 2.72 + 2.89E\text{-}5(SS)$, $r^2 = 0.55$, respectively), whereas PC-rates produced a quadratic response in pH ($pH = 4.22 + 1.33E\text{-}5(PC) - 4.95E\text{-}11(PC)^2$, $R^2 = 0.82$) when applied to IMC-PG. Similarly, a linear increase in pH

Table 2. Preplant pH, electrical conductivity, and Mehlich-I extractable nutrient data for IMC-PG treated with dolomite, phosphatic clay, and sewage sludge.[1]

Amendment Rate, g/kg	pH	EC, dS/m	Calculated[2] EC_e, dS/m	Concentration, mg/kg Mg	K	P	Zn	Cu	Mn	Fe
None										
0	2.78	4.16	17.9	25	39	664	1.3	0.79	1.2	18
Dolomite										
0.87	2.84	4.34	19.3	61	42	792	1.1	0.91	1.4	18
1.74	2.91	4.21	18.3	90	41	923	1.2	1.09	2.0	30
3.48	3.18	3.93	16.0	158	41	980	0.7	0.75	1.2	28
6.96	4.34	3.87	15.6	326	48	1193	1.4	1.13	1.3	65
C.V.	2.0	7.0		32	17	22	21	23	34	47
Contrasts										
0 vs Dolo[3]	*	ns		*	ns	ns	ns	ns	ns	ns
0.87 vs 1.74	ns	ns		ns	ns	ns	ns	ns	ns	ns
1.74 vs 3.84	*	ns		*	ns	ns	*	*	*	ns
3.48 vs 6.96	*	ns		*	ns	ns	*	*	ns	*
PC										
21.7	4.44	2.84	7.32	95	45	1129	1.5	1.12	1.8	76
43.5	4.80	2.72	6.36	184	50	1515	1.5	0.90	2.7	94
87.0	4.95	2.90	7.80	304	63	2066	1.8	0.83	4.3	92
174.0	5.03	3.07	9.16	346	62	2039	1.7	0.73	4.6	58
C.V.	1.2	3.8		23	17	17	26	21	21	14
Contrasts										
0 vs PC[3]	*	*		*	*	*	ns	ns	*	*
21.7 vs 43.5	*	ns		*	ns	ns	ns	ns	ns	*
43.5 vs 87.0	*	ns		*	ns	*	ns	ns	*	ns
87.0 vs 174.0	ns	ns		ns	ns	ns	ns	ns	ns	*
SS										
4.35	2.88	4.10	17.4	30	42	765	3.1	1.38	1.4	23
8.70	2.93	3.92	16.0	33	38	737	4.1	1.94	1.4	24
17.40	3.24	4.14	17.7	45	44	843	8.1	2.79	1.8	53
C.V.	3.0	9.7		31	21	24	44	17	33	59
Contrasts										
0 vs SS[3]	*	ns		ns	ns	ns	*	*	ns	*
4.35 vs 8.70	ns	ns		ns	ns	ns	ns	*	ns	ns
8.70 vs 17.40	*	ns		ns	ns	ns	*	*	ns	*

[1] Mean of 4 replicates.
[2] Calculated EC_e = (EC - 2.20) x 8 + 2.20.
[3] Dolo, PC, SS = compared with the average of all dolomite, all PC, or all SS rates.
* = Significantly different at 0.05 level of probability.
ns = Not significantly different at 0.05 level of probability.

Table 3. Preplant pH, electrical conductivity, and Mehlich-I extractable nutrient data for ET-PG treated with dolomite, phosphatic clay, and sewage sludge.[1]

Amendment Rate, g/kg	pH	EC, dS/m	Calculated[2] EC_e, dS/m	Concentration, mg/kg Mg	K	P	Zn	Cu	Mn	Fe
<u>None</u>										
0	4.82	2.29	2.92	8	3.3	89	0.44	0.33	0.15	5
<u>Dolomite</u>										
0.22	5.03	2.29	2.92	15	4.6	76	0.61	0.40	0.15	4
0.43	4.95	2.28	2.84	21	5.3	74	0.57	0.47	0.15	4
0.87	5.13	2.28	2.84	49	2.2	70	0.74	0.38	0.19	5
1.74	5.12	2.29	2.92	64	3.0	71	0.64	0.42	0.20	6
C.V.	2.0	0.6		17	65	11	34	39	29	21
<u>Contrasts</u>										
0 vs Dolo[3]	*	ns		*	ns	*	ns	ns	ns	ns
0.22 vs 0.43	ns	ns		ns	ns	ns	ns	ns	ns	ns
0.43 vs 0.87	*	ns		*	ns	ns	ns	ns	ns	ns
0.87 vs 1.74	ns	ns		*	ns	ns	ns	ns	ns	ns
<u>PC</u>										
0.87	5.04	2.28	2.84	5	3.2	93	0.46	0.32	0.17	6
1.74	5.06	2.28	2.84	8	2.8	119	0.44	0.28	0.20	6
3.48	5.19	2.28	2.84	14	3.2	156	0.46	0.32	0.25	7
6.96	5.27	2.30	3.00	25	3.9	231	0.47	0.32	0.44	12
C.V.	1.0	0.6		11	46	7	30	33	19	17
<u>Contrasts</u>										
0 vs PC[3]	*	ns		*	ns	*	ns	ns	*	*
0.87 vs 1.74	ns	ns		*	ns	*	ns	ns	ns	ns
1.74 vs 3.48	*	ns		*	ns	*	ns	ns	ns	ns
3.48 vs 6.96	*	*		*	ns	*	ns	ns	*	*
<u>SS</u>										
0.87	4.98	2.30	3.00	5	3.7	84	1.48	0.44	0.25	10
1.74	5.04	2.33	3.24	5	3.4	111	1.89	0.62	0.23	47
3.48	5.07	2.37	3.56	6	3.6	133	3.09	0.82	0.32	83
C.V.	2.1	0.7		20	42	14	34	26	63	34
<u>Contrasts</u>										
0 vs SS[3]	*	*		ns	ns	*	*	*	ns	*
0.87 vs 1.74	ns	ns		ns	ns	*	ns	ns	ns	*
1.74 vs 3.48	ns	*		ns	ns	ns	*	ns	ns	*

[1] Mean of 4 replicates.

[2] Calculated EC_e = (EC - 2.20) x 8 + 2.20.

[3] Dolo, PC, SS = compared with the average of all dolomite, all PC, or all SS rates.

* = Significantly different at 0.05 level of probability.

ns = Not significantly different at 0.05 level of probability.

was observed for PC rates (pH = 5.01 + 3.86E-5(PC), r^2 = 0.54) added to ET-PG.

For the IMC-PG, approximately five times the quantity of SS as compared to dolomite was required to raise the pH to an equivalent level. Similarly, for the ET-PG, four times the quantity of PC and SS was required to raise the pH, compared to dolomite. For the IMC-PG, approximately 16 mt/ha dolomite and 50 mt/ha PC would be required to raise the pH above 4.0.

Dry Matter Yield (DMY) and Aerial Biomass Nutrient Content

For the IMC-PG (table 4), a linear increase in DMY was produced by the PC rates (DMY = 0.46 + 6.20E-5(PC), r^2 = 0.81). However, no growth at all was observed on the SS-treated PG, nor on any but the highest dolomite rate. The DMY for the highest dolomite rate was low despite sufficient nutrients, suggesting that salinity (15.6 dS/m) may have affected growth after germination. Both PC and SS rates produced a linear increase in DMY with application to ET-PG (DMY = - 0.039 + 1.00E-4(PC), r^2 =0.50 and DMY = -0.015 + 1.27E-4(SS), r^2 = 0.46, respectively), though DMY for both the PC and SS rates were lower than for the inorganically fertilized PG. When the pH was less than 4.3, no growth was observed. Richardson (1992) observed bermudagrass growth at pH 3.9 or higher on limed PG, but found no difference in yield despite higher pH values.

Tissue-nutrient levels from IMC-PG grown plants were within sufficiency ranges suggested by Jones (1980), whose nutrient sufficiency ranges were used for comparative purposes in this study. However, Mg was much lower than the critical level of 2.0 g/kg for the lowest PC rate. Low DMY at this rate may have been due to Mg deficiency as suggested by the concentration in the tissue. For ET-PG, tissue Mg concentrations were below the critical level for all plants grown on SS, for the lowest PC rate, and for the inorganic-fertilizer treated PG. Tissue K was also below the critical level of 10 g/kg for all amendments, including PG that

Table 4. Dry matter yield and nutrient concentrations of bermudagrass grown on IMC-PG treated with dolomite and phosphatic clay.[1]

Amendment Rate, g/kg	DMY, g/pot	Concentration						
		Mg	K	P	Zn	Cu	Mn	Fe
		g/kg			mg/kg			
Dolomite								
6.96	0.17	2.1	32	6.5	55	16.4	148	52
PC								
21.7	0.30	0.8	15	10.7	40	16.1	68	34
43.5	4.31	1.2	13	8.3	32	6.0	53	33
87.0	6.85	1.8	11	8.8	21	5.8	54	31
174.0	10.74	2.8	11	7.2	27	6.0	63	38
C.V.	33	14	42	21	16	47	14	8
Contrasts								
21.7 vs 43.5	*	*	ns	ns	*	*	*	ns
43.5 vs 87.0	*	*	ns	ns	*	ns	ns	ns
87.0 vs 174.0	*	*	ns	ns	ns	ns	ns	*

[1] No growth or dry matter yield obtained for any of the other amendments or rates.
* = Significantly different at 0.05 level of probability.
ns = Not significantly different at 0.05 level of probability.

Table 5. Dry matter yield and nutrient concentrations of bermudagrass grown on ET-PG treated with dolomite, phosphatic clay, and sewage sludge.

Amendment Rate, g/kg	DMY, g/pot	Mg	K	P	Zn	Cu	Mn	Fe
		Concentration						
		g/kg			mg/kg			
None								
0	4.18	1.3	5.6	6.3	51	6.9	12	28
Dolomite								
0.22	4.39	1.6	4.2	5.8	57	6.8	16	24
0.43	4.62	1.9	3.3	4.5	40	5.2	16	27
0.87	4.04	2.1	4.2	4.2	37	4.8	15	29
1.74	3.32	1.9	5.2	4.4	56	5.2	19	27
C.V.	20	16	17	12	21	16	17	16
Contrasts								
0 vs Dolo[2]	ns	*	*	*	ns	*	*	ns
0.22 vs 0.43	ns	ns	ns	*	*	*	ns	ns
0.43 vs 0.87	ns	ns	ns	ns	ns	ns	ns	ns
0.87 vs 1.74	ns	ns	ns	ns	*	ns	ns	ns
PC								
0.87	0.10	1.2	3.6	4.3	101	4.5	25	41
1.74	0.05	2.3	3.6	5.1	167	2.5	60	48
3.48	0.34	1.8	3.0	4.4	246	5.3	39	38
6.96	0.60	2.1	2.5	4.3	144	4.8	38	37
C.V.	29	17	18	9	34	34	16	21
Contrasts								
0 vs PC[2]	*	*	*	*	*	*	ns	*
0.87 vs 1.74	ns	*	ns	ns	ns	ns	*	ns
1.74 vs 3.48	ns	ns	ns	ns	*	ns	*	ns
3.48 vs 6.96	ns	ns	ns	ns	*	ns	ns	ns
SS								
0.87	0.17	0.9	4.1	5.1	183	6.6	26	46
1.74	0.10	0.8	2.3	4.0	187	6.8	20	45
3.48	0.46	0.8	3.2	3.8	236	7.6	33	58
C.V.	18	20	17	15	22	23	15	35
Contrasts								
0 vs SS[2]	*	*	*	*	*	ns	*	*
0.87 vs 1.74	ns	ns	*	ns	ns	ns	*	ns
1.74 vs 3.48	*	ns	ns	ns	ns	ns	ns	ns

[2] Dolo, PC, SS = compared with the average of all dolomite, all PC, or all SS rates.
* = Significantly different at 0.05 level of probability.
ns = Not significantly different at 0.05 level of probability.

received only inorganic fertilizer. The low DMY in PC-amended ET-PG may be attributed to K deficiency, while that in SS-amended ET-PG may be due to both Mg and K deficiencies. Recently, Shahandeh and

Sumner (1993) reported that fertilization with 150 mg/kg K, along with 100 mg/kg N and 12 mg/kg Mg, resulted in the best total plant growth for a mixture of weeping lovegrass (Eragrostis curvula) and lespedeza (Lespedeza cuneata) grown in artificially leached PG that had a pH of 4.1. Bermudagrass tissue concentrations in PC- and SS-treated ET-PG showed Mn and Fe to be adequate, but Mn and Fe were below the sufficiency range for all dolomite rates. Despite having comparable Mg and K concentrations in its tissue, the PC treated ET-PG showed much less growth than the dolomite treated PG. A twofold to fivefold increase in Zn concentration was also observed with PC and SS applications, which seems to suggest possible Zn toxicity to bermudagrass. However, Sartain (1992) reported that Zn applications did not affect bermudagrass growth despite tissue concentrations ranging from 124 to 355 mg/kg Zn.

Conclusions

Bermudagrass germination and growth on PG occurs at pH around 4.0. This study showed germination and growth on PG at pH 4.3 while Richardson (1992) reported growth at pH 3.9. Phosphogypsum pH influences seed germination and growth to a larger extent than salinity. Chemical-fertilizer rates of Mg and K used in this study were not sufficient to adequately provide the needed amounts of these nutrients for optimum plant growth, based on tissue analyses. Dolomite was effective in raising the pH and supplied Mg. Phosphatic clays reduced the effects of salinity on plants growing in recently decommissioned stacks that are generally higher in salts than older, leached stacks. The PC was also effective in increasing pH and added nutrients such as Mg, K, Mn, and Fe. Sewage sludge also increased pH and supplied nutrients such as Zn, Cu, and Fe. Dolomite, PC, and SS have potential for use as nutrient sources and also for raising pH. Application rates of amendments will have to be higher than those used in this study to provide adequate nutrients for plant growth in older, leached stacks, and to increase pH in recently deactivated stacks.

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