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Plant uptake of major and trace elements from soils amended with a high-calcium dry flue gas desulfurization by-product

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HIGHLIGHTS

- Increasing rates of a DFGD by-product increased plant tissue concentrations of nutrients and trace elements.
- Soil pH, and concentrations of nutrients and trace elements increased with increasing application rate.
- The high-Ca DFGD by-product used in this experiment was an effective nutrient source and liming material.
- Caution should be used to avoid over liming the soil and increasing tissue Se concentrations above limits deemed safe for grazing cattle.

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ABSTRACT

Coal combustion by-products (CCBs) are a potentially valuable source of essential plant nutrients, but CCBs also frequently contain trace elements. The objective of this greenhouse study was to evaluate the effects of soil and application rate of a high-calcium (Ca) dry flue gas desulfurization (DFGD) by-product on Bermudagrass (*Cynodon dactylon* L.) growth and plant tissue and soil composition. Surface horizons of two soils with contrasting texture were mixed with a high-Ca DFGD by-product at rates of 0, 2.5, 5, 10, and 15 Mg ha^{-1}. Bermudagrass was allowed to grow in the soils for 119 days. Concentrations of plant nutrients and selected trace elements were determined in soil and plant tissue. Plant dry matter and tissue concentrations of Ca, Mg, B, Se, Rb, and U increased as DFGD application rate increased. Concentrations of Mehlich-3-extractable soil P, Ca, Mg, S, Na, Fe, and B and strong-acid-extractable V and Hg increased with increasing application rate. Soil pH increased with application rate and electrical conductivity was only greater than that in the control at the 15 Mg ha^{-1} application rate after 119 days. The DFGD by-product used in this study can be beneficially reused as a soil amendment provided soil pH and plant tissue Se concentrations are closely monitored.

1. Introduction

It is estimated that more than 100 million Mg of coal combustion by-products (CCBs) are produced each year, making the mass of coal combustion wastes produced annually second only to that of municipal solid wastes [17]. In 2014 only 52% of the CCBs generated in the United States were used beneficially, which left 51 million Mg to be disposed of in landfills or surface impoundments [2]. The 1990 Clean Air Act Amendment mandated that sulfur dioxide (SO_2) emissions from coal-fired power plants be reduced by 1995. The mandated reduction in SO_2 from coal-fired power plants has resulted in the production of flue gas desulfurization (FGD) by-products with physio-chemical characteristics that differ from those of previously produced fly ash.

Flue gas desulfurization by-products are formed when emissions control processes inject a calcium sorbent into the flue gases to trap and remove SO_2 from emissions streams. Dry FGD (DFGD) systems often remove SO_2 and fly ashes simultaneously, resulting in a by-product that is a mixture of fly ash, unreacted sorbent, calcium sulfite ($CaSO_3{\cdot}0.5H_2O$), anhydrite ($CaSO_4$) and gypsum ($CaSO_4{\cdot}2H_2O$) [16]. Since they contain unspent sorbent, DFGD

Abbreviations: CCB, coal combustion by-product; FGD, flue gas desulfurization; DFGD, dry flue gas desulfurization; DM, dry matter; ICP-MS, inductively coupled plasma-mass spectrometry; EPA, Environmental Protection Agency; LSD, least significant difference; NRC, National Research Council; MCL, maximum contaminant level; MCLG, maximum contaminant level goal; AWRC, Arkansas Water Resources Center; SWEPCO, Southwestern Electric Power Company.

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by-products are typically alkaline and have the potential to be used as substitutes for agricultural lime. Dry FGD by-products containing Class-C fly ash can have particularly large Ca concentrations and are often described as high-Ca DFGD by-products. Several studies have demonstrated the ability of DFGD by-products to neutralize soil acidity and increase soil pH [6,11,23]. Although calcium carbonate ($CaCO_3$) is commonly used to alleviate soil acidity, relative insolubility makes $CaCO_3$ effective only at the site of incorporation. The presence of liming materials, such as $Ca(OH)_2$ and CaO in DFGD by-products, which are significantly more soluble than $CaCO_3$, provide greater potential for mitigating soil acidity beyond the site of incorporation [9].

Flue gas desulfurization by-products also contain essential plant nutrients and can improve soil nutrient status when used as a soil amendment. Kost et al. [16] analyzed the chemical and physical properties of 59 DFGD by-products from 13 locations and reported that Ca, S, Al, Fe and Si were the major matrix elements. The DFGD by-products analyzed also had significant concentrations of Ca, Mg, Fe, S, B, Cu, Mn, Ni, P, and Zn. Trace amounts of Mo and K were also present in the DFGD by-products. Several studies have reported increased nutrient uptake by plants grown in soil amended with a DFGD by-product [10,11,22,21,6,7,8,26].

Although DFGD by-products are potentially useful soil amendments, the presence of potentially phytotoxic trace elements and soluble salts is a cause for possible concern [9,16,1,3]. In addition, the chemical composition of DFGD by-products continuously change as emission control technologies evolve. Therefore, it is imperative that each new generation of by-products be examined in order to assess potential environmental impacts resulting from land application. Punshon et al. [21] reported increased leaf and root tissue concentrations of As, Mo, and Se and decreased leaf and root tissue Pb concentration in corn (*Zea mays*), cotton (*Gossypius hirsutus*), soybean (*Glycine* max) and radish (*Raphanus sativus*) grown on soil amended with a FGD residue. Chen et al. [6] reported increased As and Hg concentrations in alfalfa (*Medicago sativa*) tissue, but decreased Cd, Cr, and Pb tissue concentrations compared to an unamended control. The goal of this greenhouse experiment was to determine if a high-Ca DFGD by-product can be used as a soil amendment without adversely impacting plant growth, plant composition, or soil quality. Therefore, the objective of this greenhouse study was to evaluate the effects of soil and application rate of a high-Ca DFGD by-product on bermudagrass (*Cynodon dactylon* L.) growth and plant tissue and soil composition.

2. Materials and methods

Soils used in the study were from the top 10 cm of the A horizon of a Roxana fine sandy loam (coarse-silty, mixed, superactive, non-acid, thermic Typic Udifluvents) collected from the University of Arkansas, Division of Agriculture's Vegetable Substation near Kibler, Arkansas and the 10 cm of the A horizon of a Captina silt loam (fine-silty, siliceous, active, mesic Typic Fragiudults) collected from the Arkansas Agricultural Research and Extension Center in Fayetteville (Table 1). The DFGD by-product used in this study (Table 2) was obtained from Southwestern Electric Power's Turk Plant in southwestern Arkansas. The John W. Turk Power Plant utilizes an Alstom Novel Integrated Desulfurization design and burns subbituminous coal from the Powder River Basin in Wyoming (personal communication, Mark Cantrell, Arkansas Electric Power, 2015). After air-drying, grinding, and sieving through a 2-mm mesh screen, soil was thoroughly mixed with powderized DFGD at rates equivalent to 0, 2.5, 5, 10 or 15 Mg/ha on a dry-weight basis.

Table 1
Initial soil characteristics of a Captina silt loam and Roxana sandy loam collected from the 0–10 cm depth prior to amendment with a high-Ca dry flue gas desulfurization by-product.

Soil Property	Soil Texture	
	Silt Loam	Sandy Loam
Sand ($g\,g^{-1}$)	0.41	0.52
Silt ($g\,g^{-1}$)	0.56	0.42
Clay ($g\,g^{-1}$)	0.03	0.06
Organic Matter (%)	1.2	1.1
pH (2:1)	6.7	7.2
Electrical Conductivity ($\mu S\,cm^{-1}$)	62.8	41.6
Mehlich-3 Extractable ($mg\,kg^{-1}$)		
P	30.5	65.5
K	48.4	46.3
Ca	805	798
Mg	31.6	101
S	7.0	4.6
Na	10.5	10.0
Fe	165	205
Mn	74.5	55.3
Zn	5.3	2.9
Cu	0.5	1.0
B	0.2	0.1
Trace Elements ($mg\,kg^{-1}$)		
V	10.41	9.85
Cr	14.56	8.70
Co	2.65	3.08
Ni	1.5	5.14
As	2.28	2.39
Se	0.67	0.91
Rb	3.15	3.73
Cd	0.07	0.09
Cs	0.50	0.51
Hg	0.04	0.02
Pb	10.01	7.53
Th	2.06	2.92
U	1.05	0.80

Table 2
Summary of mean (n = 3) chemical characteristics of a high-Ca dry flue gas desulfurization by-product collected from the John W. Turk Power Plant in Hempstead County, Arkansas.

Parameter	Mean (standard error)
pH	10.6 (0.29)
Electrical Conductivity ($mS\,cm^{-1}$)	2.4 (0.24)
Major Elements ($g\,kg^{-1}$)	
P	10.3 (0.67)
K	4.7 (0.32)
Ca	410 (0.14)
Mg	49.8 (0.19)
S	89.7 (0.17)
Na	14.1 (0.11)
Fe	64.2 (0.13)
Mn	0.2 (0.01)
Zn	0.3 (0.01)
Cu	0.2 (0.01)
B	1.0 (0.02)
Trace Elements ($mg\,kg^{-1}$)	
V	138 (0.74)
Cr	81.1 (0.21)
Co	16.9 (0.21)
Ni	43.1 (0.13)
As	13.3 (0.06)
Se	12.9 (0.10)
Rb	1.4 (0.01)
Cd	0.4 (0.01)
Cs	1.3 (0.12)
Hg	0.8 (0.01)
Pb	0.2 (0.02)
Th	3.4 (0.02)
U	5.3 (0.01)