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Abstract
Flue gas desulfurization (FGD) gypsum was recently approved for use in Kansas as a sulfur (S) fertilizer and as a soil amendment. Gypsum has been known as an effective product used in remediation of sodic soils, as the calcium (Ca) can exchange with sodium (Na) on the cations on clay particles. Marketing efforts have promoted the use of FGD gypsum on non-sodic soils as a means of improving soil health. Two 3-year study sites were established in Kansas in 2013, and no yield effects were observed for any of the site years. Treatment differences for grain quality and soil chemical properties had consistently greater sulfate-sulfur (SO_4-S) with increasing FGD application rates. Soil electrical conductivity (EC) had instances where it was greater with increasing gypsum rates. There were no treatment differences for the selected soil physical and biological parameters. During this project, FGD gypsum did not cause changes in soil health at the two sites.

Keywords
gypsum, soil, soil health, soil management, corn, soybean

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Summary

Flue gas desulfurization (FGD) gypsum was recently approved for use in Kansas as a sulfur (S) fertilizer and as a soil amendment. Gypsum has been known as an effective product used in remediation of sodic soils, as the calcium (Ca) can exchange with sodium (Na) on the cations on clay particles. Marketing efforts have promoted the use of FGD gypsum on non-sodic soils as a means of improving soil health. Two 3-year study sites were established in Kansas in 2013, and no yield effects were observed for any of the site years. Treatment differences for grain quality and soil chemical properties had consistently greater sulfate-sulfur (SO_4-S) with increasing FGD application rates. Soil electrical conductivity (EC) had instances where it was greater with increasing gypsum rates. There were no treatment differences for the selected soil physical and biological parameters. During this project, FGD gypsum did not cause changes in soil health at the two sites.

Introduction

Coal-burning power plants produce FGD gypsum in the process of removing S from air emissions, and is approved for land-application as a beneficial soil amendment in Kansas and many other states. Its beneficial uses include as an S fertilizer source, as one ton of gypsum contains 372 pounds of S. Crop response to gypsum has been highly variable in studies around the US (Buckley and Wolkowski, 2012). Other uses include the ability to flocculate clays in a sodic soil, which can lead to improved physical properties. What is not known is the potential for FGD gypsum to improve soil health in average or normal cropland soils. Previous work by Norton and Dontsova (1998) concluded that gypsum could flocculate clay particles in soils with relatively high exchangeable magnesium (Mg). The objective of this project is to evaluate the potential benefits of FGD gypsum on two average fields, with respect to crop yield, grain quality, and soil health.

Procedures

The study was initiated in the spring of 2013, continued in 2014, and completed in 2015 at the end of the growing season. One trial was located at the East Central Kansas Experiment Field near Ottawa, Kansas, located on a Woodson silt loam soil, and no-tilled for 10+ years before the study was initiated. Gypsum was applied by hand broadcasting and plots were 15 feet wide by 30 feet long with four replications in a randomized complete block design. The second trial was conducted on a farmer's field near Goessel, Kansas, in cooperation with a local cooperative, mapped as Wells loam and

Ladysmith silty clay loam. Alfalfa was grown for its fifth season in 2013 and terminated by herbicide, then wheat was no-tilled in fall 2013, and the field remained no-till for the duration of the experiment. Strips were 90 feet wide and 2,640 feet long, and FGD was applied using a commercial spreader and prescription map. The Goessel site layout was a strip block design with three replications. Application rates of FGD gypsum at both sites were as follows: 0 (control), 0.5 t/a/yr, 1 t/a/yr, 2 t/a/yr, and a one-time application of 2 t/a prior to the 2013 growing season.

Crops were harvested using a small plot combine at the Ottawa site and with the cooperating farmer's combine at the Goessel site. Grain samples were retained from the Ottawa site and submitted to a commercial testing laboratory for feed analysis characterization.

Soil samples and measurements were collected in October 2013, March 2015, and November 2015. Physical properties evaluated include bulk density for the 0-6, 6-18, and 18-36 in. depth intervals, wet aggregate stability for the 0-3 in. depth interval, and double ring infiltration. Prior to each infiltration measurement, the soils were saturated for 12 hours. The rings were refilled the next morning to a depth of eight inches and infiltration was measured for three hours. Chemical analyses were performed for the 0-6, 6-18, and 18- 6 in. depth intervals for pH, Mehlich P, electrical conductivity, cation exchange capacity by summation method, Cl, SO_4-S, total N, and total C. Samples were collected from the 0-6 in. soil depth in fall 2013 and fall 2015 after crop harvest for the Haney testing package and microbial community composition by phospholipid fatty acid analysis (PLFA). Biological samples were shipped overnight to a commercial soil testing laboratory (Ward Laboratories, Kearney, NE).

The analysis of variance was conducted using the PROC MIXED procedure in SAS v 9.4 (SAS Institute, Inc., Cary, NC). Least square means at the 0.05 significance level were computed to test the differences among treatments.

Results

No treatment effects were observed for crop yields in the duration of the study (Tables 1 and 2). Grain nutrient content was evaluated for the Ottawa location only, and for the 2013 corn and 2014 soybeans there were no treatment differences for any of the properties measured. For the 2015 corn grain, if considered at the $p < 0.1$ level, the grain from the 2 t/a/yr rate had greater S concentration than the control and 1 t/a/yr treatments. Also, if considered at the $p < 0.1$ level, the one-time, 2 t/a treatment had the greatest grain boron (B) content and was significantly more than the control and the 1 t/a/yr treatments.

Electrical conductivity at Ottawa and SO_4-S at both sites (Table 3) were the soil chemical parameters for which treatment differences were observed most frequently, generally increasing with increasing FGD gypsum applications and highest for the 2 tons per acre per year rate.

There were no statistically significant differences in soil physical properties (Table 4) for any of the site years in this project. The double ring infiltration rates at the Ottawa site were much faster for the fall 2013 measurements as compared to spring and fall 2015.

For the fall 2013 Ottawa measurement, the FGD treatments were numerically greater than the control; however, large variability was present and the p-value of 0.76 reflects that. For the spring and fall 2015 sampling, the infiltration rates were slower, but generally increased with increasing FGD gypsum application rates. The Goessel infiltration rates averaged less than 1 cm per hour for the spring 2014 and 2015 samplings but averages 2.7 cm per hour with no trends with respect to FGD application rate; however, for the fall 2015 period the FGD gypsum treated plots had faster infiltration rates than the control, though not statistically significant.

Bulkest density and wet aggregate stability mean weight diameters (MWD) were not statistically significant with respect to FGD gypsum rates for any of the sampling periods at either site, and there were no trends with respect to rates. The MWD is highly dependent upon the soil conditions at sampling such as the season and place within the crop rotation (Stone and Schlegel, 2009).

No treatment effects were observed for soil biological properties (Table 5) in the duration of the study at either site. Ottawa 2013 and 2015 were both collected following corn harvest in November, prior to a hard frost, and had an overall average diversity index of 1.4, which is considered slightly above average. The Goessel samples were collected in May 2014 in a nearly mature wheat crop prior to grain harvest, and averaged 1.5, which is rated good for diversity index. The fall 2015 Goessel samples were collected in early November. The 2015 grain crop had been soybeans, and at the time of soil sampling, young winter wheat was growing. The diversity index for this sampling period averaged 1.6, which rates as very good for diversity index. However, Frostegard et al. (2011) stated that "the use of PLFA data to calculate diversity indices and then trying to interpret these are flawed approaches and should not be used."

There were also no treatment differences for the Haney number. According to information provided by the testing laboratory, the Haney soil health number is defined as: 1-day CO_2-C divided by the organic C:N ratio plus the water extractable organic carbon/100 + water extractable organic nitrogen/10. The calculation combines 5 independent soil measurements and varies from 0 to more than 50. No rating scale was provided; however, the laboratory biological testing manager stated that the laboratory considers scores >7 an indicator of a healthy soil (Lance Gunderson, personal communication). The Haney number averaged 8.7 and 12.0 for the fall 2013 and 2015 Ottawa samples, respectively. The Haney number averaged 14.3 and 16.2 for the spring 2014 and fall 2015 Goessel samples, respectively. Due to the limited number of sampling periods, it may not be appropriate to assume that the increase in Haney numbers indicates an increase in soil health over time, particularly because the Goessel site was sampled in different seasons and timing during a crop rotation. (At the time of this writing, no peer-reviewed journal articles were found to define the Haney soil health number).

The application of FGD gypsum did not have significant crop yield effects in this three year, two site study in Kansas. Few soil parameters were consistently influenced other than SO_4-S at both sites, and EC at Ottawa only. There were no improvements to soil physical or biological parameters. Based upon these findings, the use of FGD gypsum for the purpose of improving the soil health of normally functioning agricultural soils would not be recommended. With no apparent agronomic or soil health incentive, the likelihood of producers purchasing and applying such a large rate of gypsum is unlikely.

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Table 1. Crop yield and grain characterization, Ottawa, KS, research location

2013: Corn

FGD Gyp.	Yield	N	P	K	S	Fe	Mn	Cu	B	Mo
t/a/yr	bu/a	%	ppm							
0	152.0	1.43	0.25	0.48	0.14	76	6	3.15	4.7	0.08
0.5	143.2	1.47	0.24	0.44	0.15	128	7	3.2	4.7	0.10
1	145.1	1.42	0.25	0.43	0.15	222	7	3.3	4.4	0.23
2	151.6	1.42	0.25	0.44	0.15	95	8	3.1	4.8	0.14
2 t once	152.3	1.52	0.25	0.43	0.16	181	7	3.3	5.3	0.20
p-value	*0.84*	*0.14*	*0.96*	*0.80*	*0.21*	*0.55*	*0.30*	*0.99*	*0.86*	*0.80*

2014: Soybeans

FGD Gyp.	Yield	Cr. Prot.	P	K	S	Fe	Mn	Cu	B	Mo	Fat
t/a/yr	bu/a	%	ppm								Oil, %
0	45.7	38.8	0.42	1.80		85	26	12.6		0.43	22.0
0.5	47.6	38.9	0.40	1.75		100	26	12.4		0.31	22.0
1	45.7	38.6	0.42	1.76		83	27	12.4		0.37	21.8
2	43.5	39.0	0.42	1.77		90	26	12.5		0.31	22.1
2 t once	48.5	38.9	0.41	1.78		102	27	12.4		0.38	22.1
p-value	*0.48*	*0.61*	*0.76*	*0.67*		*0.32*	*0.81*	*0.84*		*0.13*	*0.19*

2015: Corn

FGD Gyp.	Yield	N	P	K	S	Fe	Mn	Cu	B	Mo
t/a/yr	bu/a	%	ppm							
0	124.4	1.26	0.28	0.42	0.10 B	23	5	1.3	2.9 B	0.21
0.5	138.4	1.23	0.27	0.41	0.11 AB	22	5	1.3	3.1 AB	0.19
1	134.8	1.22	0.28	0.43	0.10 B	26	6	1.4	2.8 B	0.18
2	132.5	1.22	0.27	0.41	0.11 A	21	5	1.4	3.7 AB	0.21
2 t once	125.6	1.23	0.28	0.41	0.11 AB	25	5	1.3	4.0 A	0.21
p-value	*0.17*	*0.52*	*0.69*	*0.83*	*0.06*	*0.80*	*0.20*	*0.34*	*0.09*	*0.63*

Table 2. Crop yield for on-farm trial near Goessel, KS

FGD Gypsum	Wheat yield 2014	Soybean yield 2015
t/a/yr	bu/a	bu/a
0	27.0	48.1
0.5	25.8	48.9
1	27.5	49.1
2	26.5	48.1
2 t one application	26.1	51.1
p-value	*0.92*	*0.94*

Table 3. Selected soil chemical properties, 0-6" depth interval

Ottawa								
	Fall 2013				Fall 2015			
FGD Gyp.	pH	Mehlich P	EC	SO_4-S	pH	Mehlich P	EC	SO_4-S
t/a/yr		ppm	mS/cm	ppm		ppm	mS/cm	ppm
0	5.7 AB	26.5 AB	0.39 BC	11.1 B	5.7	55.6 A	0.26 B	10.5 B
0.5	5.6 AB	14.3 B	0.38 C	14.4 B	6.1	10.1 B	0.41 B	23.0 B
1	6.0 A	10.6 B	0.84 AB	55.6 AB	6.1	8.3 B	0.49 B	29.2 B
2	5.2 B	59.6 A	0.84 AB	63.9 AB	6.1	8.7 B	1.11 A	106.0 A
2 t once	5.3 B	35.3 AB	0.99 A	88.2 A	5.8	32 .0 AB	0.32 B	15.1 B
p-value	*0.02*	*0.09*	*0.03*	*0.04*	*0.15*	*0.06*	*0.02*	*0.02*

Goessel								
	Fall 2013				Fall 2015			
FGD Gyp.	pH	Mehlich P	EC	SO_4-S	pH	Mehlich P	EC	SO_4-S
t/a/yr		ppm	mS/cm	ppm		ppm	mS/cm	ppm
0	5.8	63.2	0.85	12.5 B	6.3	31.4	0.27	7.4 B
0.5	5.3	81.1	1.78	112.7 AB	5.5	50.5	0.32	13.6 AB
1	5.3	61.5	1.30	91.5 AB	5.8	62.4	0.34	13.7 AB
2	5.7	48.7	1.34	213.1 A	6.2	43.6	0.46	19.2 A
2 t once	5.6	69.0	0.93	47.6 B	5.9	57.0	0.41	11.7 AB
p-value	*0.37*	*0.84*	*0.54*	*0.05*	*0.21*	*0.49*	*0.65*	*0.08*

Table 4. Physical soil properties

Ottawa

FGD Gypsum	Infiltration			Bulk density		Mean weight diameter		
	------------- in/hr -------------			------- g/cm³ -------		--------------- mm ---------------		
t/a/yr	F 2013	S 2015	F 2015	F 2013	F 2015	F 2013	S 2015	F 2015
0	2.3	0.2	1.1	1.38	1.39	2.6	1.6	3.0
0.5	6.8	0.8	1.1	1.46	1.46	2.8	1.8	3.4
1	4.5	0.4	1.4	1.35	1.39	2.7	1.5	2.8
2	6.2	3.4	1.8	1.49	1.51	2.7	1.6	3.2
2 t once	3.9	0.6	1.9	1.30	1.42	2.8	1.9	3.4
p-value	*0.76*	*0.29*	*0.73*	*0.57*	*0.73*	*0.96*	*0.85*	*0.62*

Goessel

FGD Gypsum	Infiltration			Bulk density		Mean weight diameter			
	------------- in/hr -------------			------- g/cm³ -------		--------------------- mm ---------------------			
t/a/yr	S 2014	S 2015	F 2015	F 2013	F 2015	F 2013	S 2014	S 2015	F 2015
0	0.2	0.2	0.3	1.72	1.80	2.0	3.5	2.0	3.5
0.5	0.3	0.2	0.9	1.43	1.80	1.8	4.4	1.8	4.3
1	0.4	0.2	1.6	1.43	1.82	2.1	3.4	1.4	4.9
2	0.3	0.2	1.1	1.51	1.87	1.8	5.1	2.2	3.6
2 t once	0.2	0.5	1.3	1.56	1.79	2.5	5.2	1.4	4.6
p-value	*0.66*	*0.50*	*0.35*	*0.22*	*0.83*	*0.19*	*0.27*	*0.30*	*0.26*

Table 5. Biological soil properties

	Ottawa			
FGD Gypsum	Haney no.	PLFA diversity index[1]	Haney no.	PLFA diversity index
t/a/yr	Fall 2013		Fall 2015	
0	9.9	1.5	12.2	1.5
0.5	7.3	1.4	12.1	1.4
1	9.2	1.2	11.5	1.4
2	9.2	1.3	11.4	1.5
2 t once	7.8	1.5	12.9	1.3
p-value	*0.55*	*0.53*	*0.63*	*0.45*

	Goessel			
FGD Gypsum	Haney no.	PLFA diversity index	Haney no.	PLFA diversity index
t/a/yr	Spring 2014		Spring 2014	
0	14.5	1.4	15.8	1.5
0.5	12.4	1.5	16.3	1.6
1	17.0	1.5	16.3	1.6
2	13.6	1.4	15.7	1.6
2 t once	14.2	1.5	16.9	1.7
p-value	*0.57*	*0.44*	*0.87*	*0.55*

[1] Diversity index rating scale: > 1.6 excellent, 1.5+ to 1.6 very good; 1.4+ to 1.5 good; 1.3+ to 1.4 slightly above average; 1.2+ to 1.3, average; and 1.1+ to 1.2, slightly below average.