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ABSTRACT

The short- and long-term effects on soil nutrient cycling, physical properties, and biological activity of striving for higher grain yields and removing crop residues for bio-fuels production must be understood to provide more quantitative crop and soil management guidelines. This study focuses primarily on potassium (K) and sulfur (S) response by corn (*Zea mays* L.) grown for bio-energy feedstock production. Our objectives for 2009 were to evaluate (i) the performance of several S fertilizers, including liquid ammonium thiosulfate (12-0-0-26S), for corn grown in Iowa, and (ii) the use of surface or subsurface bands of N-P-K-S fluid fertilizers to optimize positional and temporal availability of nutrients. The S fertility trials targeted low organic matter Clarion soils found on eroded hill slopes. Application of 30 lb S/A increased mean plant dry weight, but did not increase whole-plant concentrations of S, which were adequate for corn at the five-leaf growth stage (V5). By mid-silk, however, S concentrations were below the sufficiency range, even when S fertilizer had been applied. Application of 30 lb S/A as 13-33-0-15S or 21-0-0-24S significantly increased grain yield more than 7 bu/A, compared to the control. Stover yields were not increased by applying S. In a separate 25-acre field study, also on the Clarion-Nicollet-Webster soil association, corn was grown using a variety of management systems including 30-in. row spacing with standard fertility management and a twin-row, high-population treatment with increased nutrient additions applied in split-applications. Analysis of V6 whole-plant and ear-leaf samples indicated that management scenario, tillage, and the amount of stover removed from the field with the 2008 harvest did not affect nutrient content. However, both N and S concentrations in ear-leaf tissue were below the critical value for all treatments. These results suggest that the soil supply of N and S was not sufficient to meet crop demand. Management scenario and tillage and did not affect corn grain yields, but plots from which corn stover was not removed always yielded less than plots from which ~50% (harvested just below the ear shank) or ~90% (harvested at a stubble height of approximately 4 inches) of the stover was removed. A combination of less fertilizer N, greater immobilization, and less mineralization where residues remained probably decreased the 2009 grain yields. Unlike 2008, the intensively managed (twin row) plots did not produce more dry stover than the standard management (control) plots. The cool, cloudy conditions in central Iowa during the growing season likely limited the performance of the twin-row treatments. Residue samples collected at harvest are currently being processed to determine nutrient composition, so that the quantity of nutrients removed can be calculated.

INTRODUCTION

Growing crops for bio-fuel production has attracted the attention of many producers – especially in the Corn Belt states. Both corn grain and stover are being evaluated as potential bio-energy feedstocks, because as pointed out by Dibb (2006), current U.S. energy policy calls for more than doubling ethanol use by 2012. To ensure that sustainable grain and stover yields meet both current and new demands, the short- and long-term effects of removing both grain and stover on soil properties must be understood. Research has shown that no-tillage can reduce the rate of residue decomposition, thus offering a mechanism to maintain soil organic carbon, even if some portion of the crop residue is removed for bio-fuel production (Perlack et al., 2005). Up to this point, the bio-fuel industry has been forced to use estimates, such as those offered by Johnson et al. (2006), to determine the amount of crop residue that must remain on the land to sustain both the farming and ethanol production enterprises. To provide more quantitative guidelines, soil management studies focusing on tillage, fertilizer rates and placement, cover crops, and other management factors are needed. Because it would be difficult to address all of these variables in a single project, this project focuses primarily on potassium (K) and sulfur (S) response by corn grown for bio-fuel production.

The effectiveness of K and S fertilizers depends on both the ability of the added material to increase the soil supply of the nutrients, and the ability of the plant to respond to this increase. Changes in the soil supply of K, resulting from fertilizer addition, depend on soil type and inherent K levels (Kovar and Barber, 1990). Unfortunately, the effect of S fertilizer application on the soil supply of S is not as well understood, primarily because mineralization of organic S complicates the determination of the plant-available S in soil (Tabatabai, 1996).

The spatial distribution of fertilized soil relative to actively growing roots is also important. Karlen and Kovar (2005) reported that deep placement of preplant K fertilizer significantly increased both soil test K and plant growth in long-term tillage plots at the Iowa State University Agricultural/Biosystems Engineering Research Center. Rehm (2005) found that a band application of dry or liquid fertilizer S near the seed furrow significantly increased corn yields when conservation tillage was used. Those results suggest that fertilizer placement can increase the positional availability of the nutrients for uptake by crop roots.

The overall goal of this project is to evaluate the use of surface or subsurface bands of N-P-K-S fluid fertilizers to optimize positional and temporal availability of K and S in order to enhance corn grain and biomass productivity. This research is part of a much larger corn grain and residue removal study that includes tillage, fertility management, plant population and geometries (single- versus twin-row), one-time application of biochar to test the “Charcoal Vision” (Laird, 2008), as well as annual and perennial cover crops. Our specific objectives for 2009 were to evaluate (i) the performance of several S fertilizers, including liquid ammonium thiosulfate (12-0-0-26S), for corn grown in Iowa, and (ii) the use of surface or subsurface bands of N-P-K-S fluid fertilizers to optimize positional and temporal availability of nutrients.

METHODS AND MATERIALS

Sulfur Study

This embedded project draws upon three years of field research conducted from 2006 through 2008, as well as a controlled-climate pot study for studying fundamental processes. Field plots were established in 2009 at the Iowa State University Kelly Research Center, northwest of Ames in Boone County, Iowa. At this location, the soil is classified as a moderately eroded Clarion loam (fine-loamy, mixed, mesic Typic Haplaquolls) with 5% to 9% slopes. Following soybean harvest in 2008, 40 lb P_2O_5/A was applied as granular 11-52-0, and 120 lb K_2O/A was applied as granular 0-0-60. The materials were incorporated by disking. Spring tillage consisted of one pass with a disk and one with a field cultivator. Plot size was 12.5 ft. by 85 ft. (0.024A). Soil samples (0-6 in.) were collected with a hand probe from each plot 16 April, and analyzed for pH, organic matter content, extractable SO^{4-}, available P, exchangeable K, Ca, and Mg, and CEC (Table 1).

The experimental design was a randomized complete block with four replications. Fertilizer treatments included (i) a control, (ii) 30 lb S/A applied as SEF (13-33-0-15S), (iii) 30 lb S/A applied as AMS (21-0-0-24S), and (iv) 30 lb S/A applied as liquid ATS (12-0-0-26S). The dry materials (treatments ii and iii) were applied as a subsurface band two inches to the side of the seed row and three inches below the soil surface, while the liquid was applied at planting as a surface dribble two inches to the side of the seed row. Six weeks after planting, N fertilizer was applied to all plots. Accounting for the N applied with the S fertilizer treatments, all plots received a total of 150 lb N/A.

Table 1. Initial soil test levels for Clarion loam in 2009. Range indicates variability among all plots in study. Soil test ratings are not available for extractable S, although values of 10 ppm are generally considered adequate.

Soil Test Parameter	Composite	Range of Values
Bray-1 P, ppm	19 (OPT)	9 (L) – 32 (VH)
Exchangeable K, ppm	113 (L)	95 (L) – 135 (OPT)
Exchangeable Ca, ppm	2016	1774 – 2247
Exchangeable Mg, ppm	204	171 – 269
Extractable S, ppm	7.1	5 – 10
pH	6.5	6.0 – 7.1
Organic Matter, %	2.3	2.0 – 2.8
CEC, cmol(+)/kg	13.2	11.2 – 16.1

Corn (Dekalb DKC61-22) was planted 24 April 2009 in 30-inch rows at a seeding rate of 36,000 plants/A. Each plot consisted of five rows. Stand counts were conducted 15 June. The effect of S fertilizer on early-season nutrient uptake was determined by analysis of whole-plant samples collected at the V5 to V6 growth stage. Ear-leaf samples were also collected at the mid-silk growth stage and analyzed for total nutrient content. The center three rows of each plot were harvested with a small plot combine equipped with a moisture meter and electronic scale to determine final yield and grain moisture. Grain and stover samples were collected by hand harvesting eight randomly selected plants from each plot. Samples were fractionated and analyzed for nutrient content.

Soil, plant, and yield data were analyzed using a general linear models (GLM) procedure of SAS (SAS Institute, 2003). Multiple comparisons among variables with significant treatment effects were tested with the Tukey-Kramer method at the 0.05 level of significance, unless otherwise noted.

Biomass Removal Study

The 25-acre field study established in 2008 on the Clarion-Nicollet-Webster soil association at the Iowa State University Agronomy & Agricultural/Biosystems Engineering Research Center (AAERC), southwest of Ames in Boone County, Iowa was continued. This study focuses on rates of residue removal (0, ~50%, and ~90%), tillage (chisel plow versus no-tillage), a one-time biochar addition, and use of annual or perennial cover crops. Because harvesting crop residue increases P, K, and S removal compared to current corn and soybean grain production systems, one set of plots (40 x 280 ft.) is managed with standard practices and a second set of plots is managed with higher inputs. Conventional weed and insect control practices are being followed. The study includes 22 treatments that are replicated four times. Soil samples (0-2 and 2-6 in.) were collected with a hand probe from each plot 19 November 2008, and analyzed for pH, organic matter content, available P, exchangeable K, Ca, and Mg, extractable SO^{4-},and CEC (Table 2). Pioneer Brand 36V75 corn was planted 4 May 2009. Fertilizer applications in 2009 were based on 2008 grain and stover removals. Early-season whole-plant samples at the V6 growth stage and ear-leaf samples at the mid-silk stage were collected and analyzed to determine the nutritional status of the crop. Crop residue and grain yields were measured using a single-pass combine with an 8-row head. Sub-samples of stover and grain are being analyzed for nutrient content so that a more complete nutrient balance can be calculated.

Table 2. Initial soil test levels in two depth increments for the Clarion-Nicollet-Webster soil association in 2009. Range indicates variability among all plots in study.

Soil Test Parameter	Composite	Range	Composite	Range
	0-2 inch		2-6 inch	
Bray-1 P, ppm	39	17 - 104	24	12 - 54
Exch. K, ppm	199	106 - 307	142	100 - 218
Exch. Ca, ppm	2112	1400 - 2830	2276	1545 - 3020
Exch. Mg, ppm	301	179 - 440	310	195 - 489
Extract. S, ppm	1.1	0.5 - 4.1	0.9	0.5 - 2.8
pH	6.5	5.9 - 7.4	6.5	5.9 - 7.0
O. M., %	3.8	2.8 - 5.3	3.7	2.9 - 4.6
CEC, cmol(+)/kg	16.0	11.0 - 22.3	16.3	11.3 - 24.9

RESULTS AND DISCUSSION

Sulfur Study

Sulfur Fertilizer Effect on Plant Nutrition

Sulfur fertilizer had no effect on plant emergence in 2009, with a mean of 93% and values ranging from 91% to nearly 100%. The early planting date did not affect seed germination or subsequent stand establishment.

Applying S to Clarion loam in 2009 affected early plant growth, but did not affect S concentrations in the plant tissue (Table 3). Application of 30 lb S/A as 13-33-0-15S increased mean plant dry weight at the V5 growth stage. A similar trend was observed when 21-0-0-24S and 12-0-0-26S were used as S sources. Application of S did not increase whole-plant concentrations of S at the five-leaf stage (Table 3), with the control and all other treatments having S concentrations in excess of 0.15%, the S level considered adequate for corn at this growth stage (Mills and Jones, 1996). Nitrogen concentrations were well above the published critical value of 3.5% (Mills and Jones, 1996), suggesting that the N applied with the S fertilizers and the soil N from the previous soybean crop were sufficient to support the corn crop before additional N was sidedressed six weeks after planting. Whole-plant P and K concentrations at V5 (Table 3) were within the sufficiency range of 0.30% to 0.50% for P and above the sufficiency range of 2.5% to 4% for K, even though the soil initially tested low in K (Table 1).

Table 3. Effect of 30 lb S/A on whole-plant dry weight, and sulfur (S), nitrogen (N), phosphorus (P), and potassium (K) concentrations at the V5 growth stage of corn grown on a Clarion loam in 2009. Values are least squares means of four replications. Values within each column followed by the same letter are not significantly different at the 0.05 level.

Treatment	Dry Weight	Nutrient			
		S	N	P	K
	g $plant^{-1}$	------------------- % --------------------			
Control	7.4b	0.22a	4.17b	0.36ab	4.61a
13-33-0-15S (SEF)	11.4a	0.23a	4.14a	0.41a	4.11a
21-0-0-24S (AMS)	8.7ab	0.24a	4.16a	0.35b	4.33a
12-0-0-26S (ATS)	8.3b	0.23a	4.04a	0.34b	4.74a

At mid-silk in 2009, no differences in ear-leaf nutrient concentrations were detected among the treatments. However, the S concentration in the tissue was below the sufficiency range of 0.21% to 0.50%, even when S was applied (Table 4). Phosphorus concentrations in ear leaves (Table 4) were in the sufficiency range (0.25% to 0.50%) for all treatments (Mills and Jones, 1996). Nitrogen and K concentrations in the leaf tissue were also within the sufficiency ranges of 2.7% to 4.0% for N and 1.7% to 3.0% for K. The problems with S uptake by the crop

Table 4. Effect of 30 lb S/A on ear-leaf sulfur (S), nitrogen (N), phosphorus (P), and potassium (K) concentrations at the mid-silk stage of corn grown on a Clarion loam in 2009. Values are least squares means of four replications. Values within each column followed by the same letter are not significantly different at the 0.05 level.

Treatment	Nutrient			
	S	N	P	K
	------------------- % --------------------			
Control	0.19a	2.99a	0.34a	2.25a
13-33-0-15S (SEF)	0.17a	2.85a	0.35a	2.28a
21-0-0-24S (AMS)	0.19a	3.02a	0.34a	2.29a
12-0-0-26S (ATS)	0.19a	2.98a	0.33a	2.27a

suggest that the soil supply in this low organic matter soil was not sufficient to meet growing crop demand. The cool growing conditions in central Iowa during July and early August

(Hillaker, 2010) may also have limited soil S mineralization as the growing season progressed. Furthermore, significant rainfall during the same period (Hillaker, 2010) may also have leached mineralized soil N and S from the profile.

Effect of Sulfur Fertilizer on Yield

In 2009, corn grain yield was increased ($p<0.05$) by an application of 30 lb S/A to the Clarion loam soil, but stover yield was not affected (Table 4). Among the S sources, an application of 30 lb S/A as 13-33-0-15S or 21-0-0-24S significantly ($p<0.10$) increased corn grain yield compared with the control treatment. An application of 30 lb S/A as 12-0-0-26S added 4 bu/A compared with the control treatment. The 2009 growing season was the fourth consecutive year of corn grain yield increases in trials conducted on eroded, low organic matter Clarion soils. At this point, no one S source has proven superior, but our results suggest that an application of 30 lb S/A is beneficial. Sulfur removals with harvested grain and stover were higher when S fertilizer was applied in 2009, suggesting that the corn crop took advantage of the increased supply of soil S. The agronomic efficiency, calculated from the increase in grain yield per unit of S applied, averaged 10 lb grain/lb S. At this level of efficiency, and assuming $4.00/bu corn, application of S fertilizer will be profitable if the cost of S is less than $0.71 per pound.

Table 5. Effect of 30 lb S/A on corn grain yields, grain moisture at harvest, and stover yields in 2009. Values are least squares means of four replications. For comparative purposes, values for least significant differences (LSD) at both the 0.05 and 0.10 levels of significance are given. Grain yield data based on machine harvest. Stover yield data based on hand harvest.

Treatment	Grain Yield†	Grain Moisture	Stover Yield
	-- bu/A --	-- % --	tons/A
Control	217	19.9	3.10
13-33-0-15S (SEF)	223	19.3	2.96
21-0-0-24S (AMS)	223	19.6	2.85
12-0-0-26S (ATS)	221	19.4	2.90
LSD (0.05)	7	1.4	0.66
LSD (0.10)	6	1.2	0.54

†Yields adjusted to 15.5 % moisture.

Biomass Removal Study

Plant Nutrition

Management scenario, tillage, and the amount of residue removed from the field with the 2009 harvest did not affect nutrient content of whole plants at the V6 stage, and levels of all primary and secondary macro-nutrients were adequate for optimal growth (Table 6). As with the S fertilizer study, N concentrations were well above the published critical value of 3.5% (Mills and Jones, 1996), suggesting that pre-plant N fertilizer and soil N were sufficient to support the corn crop before additional N was sidedressed six weeks after planting.

At mid-silk in 2009, no differences in ear-leaf nutrient concentrations were detected among the treatments (Table 7). However, both N and S concentrations in the tissue were below the critical values. Phosphorus and K concentrations in ear leaves were within the sufficiency ranges of 0.25% to 0.50% for P and 1.7% to 3.0% for K for all treatments (Mills and Jones, 1996). Once again low N and S uptake suggests that the soil supply was not sufficient to meet crop demand by mid-silk. The cool, wet growing conditions in central Iowa during July and early August (Hillaker, 2010) may have limited N and S mineralization and availability.

Corn Grain and Stover Yield

In 2009, management scenario and tillage and did not affect corn grain yields (Table 8). Grain yields, however, were significantly different depending on the amount of residue removed from the field with the 2008 harvest. Plots from which corn stover was not removed always had lower yields than those from which ~50% or ~90% was removed. This result contradicts previous work demonstrating yield decreases when plant residues were removed (Blanco-Canqui and Lal, 2009). The amount of fertilizer, particularly N, applied for each treatment is the management variable that likely affected results. Fertilizer application rates were based solely on nutrient removals by the 2008 crop. When stover was not removed, fertilizer application rates were lower (Table 8). These results suggest that a combination of less fertilizer N, increased immobilization, and less mineralization negatively affected subsequent corn grain yields.

Table 6. Nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S) critical values and concentrations in whole plants at the V6 growth stage for five management scenarios in 2009. Values (%) are means of 8 to 16 replications depending on treatment. Standard deviations are given below each mean.

Nutrient	Critical Value	Control	Biochar 1†	Biochar 2‡	Twin-Row	Perennial CC§	Annual CC
N	3.50	3.82	3.93	3.69	3.79	3.68	3.65
		0.28	0.19	0.23	0.30	0.21	0.23
P	0.30	0.46	0.46	0.46	0.45	0.41	0.40
		0.06	0.06	0.02	0.07	0.06	0.06
K	2.50	4.81	5.18	5.03	4.75	4.15	3.88
		0.61	1.13	0.94	1.11	0.53	0.59
Ca	0.30	0.52	0.51	0.50	0.53	0.47	0.47
		0.05	0.05	0.04	0.04	0.04	0.02
Mg	0.15	0.33	0.33	0.32	0.34	0.32	0.32
		0.06	0.04	0.03	0.04	0.05	0.02
S	0.15	0.22	0.21	0.21	0.21	0.19	0.19
		0.01	0.02	0.02	0.02	0.03	0.01

†4.32 tons biochar/A; ‡8.25 tons biochar/A; §CC = cover crop.

Table 7. Nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S) critical values and concentrations in ear leaves for five management scenarios in 2009. Values (%) are means of 8 to 16 replications depending on treatment. Standard deviations are given below each mean.

Nutrient	Critical Value	Control	Biochar 1†	Biochar 2‡	Twin-Row	Perennial CC§	Annual CC
N	2.70	2.41	2.29	2.42	2.30	2.42	2.45
		0.22	0.18	0.14	0.18	0.12	0.17
P	0.25	0.27	0.27	0.28	0.27	0.27	0.27
		0.03	0.03	0.03	0.03	0.03	0.01
K	1.70	1.96	1.88	2.04	1.92	1.81	1.84
		0.21	0.25	0.22	0.26	0.28	0.27
Ca	0.21	0.53	0.55	0.58	0.50	0.53	0.53
		0.05	0.06	0.04	0.06	0.04	0.06
Mg	0.20	0.29	0.30	0.31	0.30	0.29	0.30
		0.07	0.03	0.04	0.04	0.02	0.03
S	0.21	0.17	0.16	0.17	0.16	0.17	0.16
		0.02	0.02	0.02	0.02	0.01	0.02

†4.32 tons biochar/A; ‡8.25 tons biochar/A; §CC = cover crop.

The amount of dry stover collected was higher for the 90% removal (low cuts) treatments of all management scenarios (Table 8). Unlike 2008, the intensively managed (twin row) plots did not produce more dry stover than the control plots. The cool, cloudy conditions in central Iowa during the growing season (Hillaker, 2010) presumably limited the performance of the twin-row treatments. Finally, whole plants collected at physiological maturity and residue samples from the machine harvest are being processed to determine nutrient composition so that the total amount of nutrients removed can be calculated. These values will be used to guide fertilizer recommendations for 2010.

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Table 8. Corn grain and stover yields for five management scenarios in 2009 near Ames, IA. Values are means of 4 replications. Grain yields adjusted to 15.5% moisture.

Treatment	Tillage	Percent Removal	Fertilizer Applied lb/ac	Grain (bu/ac)	Stover (t/ac)
Control	No-tillage	0	160+75+60+20	146	0
Control	No-tillage	50	199+162+147+20	174	2.16
Control	No-tillage	90	202+177+162+20	195	3.59
Control	Chisel Plow	0	160+75+60+20	146	0
Control	Chisel Plow	50	199+162+147+20	196	1.89
Control	Chisel Plow	90	202+177+162+20	188	3.35
			$LSD_{(0.05)}$	12	0.84
Twin-Row	No-tillage	0	167+75+60+30	132	0
Twin-Row	No-tillage	50	211+162+147+30	188	2.46
Twin-Row	No-tillage	90	214+177+162+30	176	2.81
Twin-Row	Chisel Plow	0	167+75+60+30	135	0
Twin-Row	Chisel Plow	50	211+162+147+30	193	1.82
Twin-Row	Chisel Plow	90	214+177+162+30	192	3.26
			$LSD_{(0.05)}$	14	0.42
Biochar 1[†]	Chisel Plow	0	160+75+60+20	136	0
Biochar 1	Chisel Plow	50	199+162+147+20	195	2.03
Biochar 1	Chisel Plow	90	202+177+162+20	196	2.96
			$LSD_{(0.05)}$	12	0.80
Biochar 2[‡]	Chisel Plow	0	160+75+60+20	156	0
Biochar 2	Chisel Plow	50	199+162+147+20	188	2.24
Biochar 2	Chisel Plow	90	202+177+162+20	194	3.23
			$LSD_{(0.05)}$	8	0.78
Annual CC[§]	No-tillage	50	199+162+147+20	181	1.87
Annual CC	No-tillage	90	202+177+162+20	197	2.99
			$LSD_{(0.05)}$	NS	0.63
Perennial CC[§]	No-tillage	50	199+162+147+20	182	1.74
Perennial CC	No-tillage	90	202+177+162+20	189	3.20
			$LSD_{(0.05)}$	10	0.45

[†]4.32 tons biochar/A; [‡]8.25 tons biochar/A; [§]CC = cover crop.

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