Is Sulfur Limiting Maize Grown on Eroded Midwestern U.S. Soils?

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Abstract
The importance of adequate sulfur (S) for maize (*Zea mays* L.) production has been recognized for many years and recently confirmed by positive yield responses. We compared a granular S-enhanced fertilizer material [SEF (13-33-0-15S)], granular ammonium sulfate [AMS (21-0-0-24S)], and liquid ammonium thiosulfate [ATS (12-0-0-26S)] on eroded Clarion (Typic Haplaquolls) hill slopes in central Iowa for three years. Applying 34 kg S/ha as SEF significantly ($P \le 0.05$) increased mean V5 plant dry weight each year. AMS and ATS showed a similar but non-significant trend. Whole-plant S concentrations at V5 were generally higher than the control for all S sources. Grain yield and moisture content at harvest were not affected by S in 2006 and 2007. In 2008, 34 kg S/ha as SEF significantly increased yield by 0.76 Mg/ha. The agronomic efficiency of S (yield per unit applied) was greatest for SEF in 2006 and 2008 (12.3 and 22.5 kg grain (kg S)$^{-1}$, respectively). Below-normal precipitation during the 2006 and 2007 growing seasons and inherent soil variability presumably affected our S yield response, but overall we conclude that S may become a limiting nutrient for maize, especially if maize stover is harvested as a bio-energy feedstock.

Key Words
Sulfur fertilizer, maize, nutrient-use efficiency.

Introduction
Although S fertilization is not commonly recommended for maize production in the Midwestern U.S., the importance of adequate S has been recognized for many years (Hoeft *et al*. 1985). Recently, positive yield responses to S fertilizer have been documented (Stecker *et al.* 1995; Rehm 2005; Lang *et al.* 2006), but as in the past, responses have not been consistent. Responsive sites usually have coarse-textured soil, with relatively low organic matter, indicating that mineralization of organic S plays an important role in supplying S to crops. Under optimum soil temperature and moisture conditions, Tabatabai and Bremner (1972) showed that a significant amount of sulfate-S will be mineralized in a short period of time. However, when soils are cold in the early spring – a common occurrence in the upper Midwest – S mineralization will be reduced and plant-available sulfate levels will be lower (Rehm 2005). Furthermore, on eroded soils or where crop residues are being harvested, decreasing levels of organic matter can reduce the pool of available S, and thus increase the probability of a yield response to S fertilizer.

Once the need for S fertilizer is identified, selection of an appropriate source is the next management decision faced by growers, but few studies have been conducted to evaluate S sources. Based on limited data, maize yields following broadcast application of elemental S were no different from those receiving sulfate sources (Rehm 1984). Similarly, both fluid and dry S sources had an equal effect on maize yield (Rehm 2005), provided that seed contact was avoided. Our objective was to determine maize response to S fertilizer, using a granular S-enhanced material [SEF (13-33-0-15S)], granular ammonium sulfate [AMS (21-0-0-24S)], or liquid ammonium thiosulfate [ATS (12-0-0-26S)] on low organic matter, eroded hill slopes in central Iowa, USA.

Methods
Field plots were established during three consecutive years in central Iowa, USA, on Clarion (fine-loamy, mixed, mesic Typic Haplaquolls) loam (2006 and 2008) or silt loam (2007). The prior crop was soybean (*Glycine max* L. Merr.), and plots were left undisturbed after harvest. Spring tillage included one pass with a disk and one pass with a field cultivator. Plot size varied from 0.01 ha to 0.03 ha. Soil samples (0-15 cm) were collected with a hand probe from each plot, and analyzed for pH, organic matter content, extractable SO_4^{2-}, available P, and exchangeable K, Ca, and Mg (Table 1), according to the methods outlined by Brown (1998). The experimental design was a randomized complete block with four treatments and four replications. Fertilizer treatments were: i) control; ii) 34 kg S/ha applied as 13-33-0-15S (SEF); iii) 34 kg S/ha applied as 21-0-0-24S (AMS); and iv) 34 kg S/ha applied as liquid 12-0-0-26S (ATS). The granular

materials (treatments ii and iii) were applied at planting as a subsurface band 5 cm to the side of the seed row and 7.5 cm below the soil surface, while the liquid was applied at planting as a surface dribble 5 cm to the side of the seed row. Six weeks after planting, urea ammonium nitrate (UAN) liquid fertilizer was applied to all plots with a spoke wheel applicator. Accounting for the N applied with the S fertilizer treatments, all plots received a total of 174 kg N/ha.

Maize was planted in early May each year in 76-cm rows at a seeding rate of 74,000 plants/ha. Each plot consisted of five rows. Stand counts were conducted approximately six weeks after planting. The effect of S fertilizer on early-season nutrient uptake was determined by analysis of whole-plant samples collected at the five-leaf (V5) 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 yield and grain moisture. To compare nutrient-use efficiency among the S sources, the agronomic efficiency (AE) of the S fertilizers was calculated with Eq. 1:

$$AE = (GW_F - GW_U)/SF \qquad (1)$$

where GW_F is grain weight from a fertilized plot, GW_U is grain weight from the control plot, and SF is the amount of S fertilizer applied.

Table 1. Mean initial soil test levels for Clarion loam and silt loam.

Soil Test Parameter	Mean	Range†
Available (Bray-1) P, mg/kg	29 (VH)	13 (OPT) – 55 (VH)‡
Exchangeable K, mg/kg	140 (OPT)	98 (L) – 146 (H)
Exchangeable Ca, mg/kg	2423	2178 – 4052
Exchangeable Mg, mg/kg	291	322 – 540
Extractable S, mg/kg	5.9	1 – 13
pH	6.7	5.5 – 7.4
Organic Matter, g/kg	26	19 – 44

† Range documents variability encountered among individual plots.
‡ Soil-test ratings, such as those for P and K, are not available for extractable S, although 10 mg/kg is generally considered sufficient.

Results and Discussion

With few exceptions, S availability and organic matter content at our sites were low, while other nutrient levels were adequate for maize production (Table 1). Subsoil levels of extractable S did not increase significantly with depth, as shown for the Clarion loam in 2006 (Figure 1). Applying S had no effect on seedling emergence, which averaged 88%, 87%, and 87% in 2006, 2007, and 2008, respectively. This was expected, since the materials were not placed in the seed furrow. Sulfur addition did affect early plant growth, as well as nitrogen (N) and S concentrations (Table 2). Applying 34 kg S/ha as SEF significantly increased mean V5 plant dry weight in all three years. Ammonium sulfate and ATS also tended to increase plant dry weight, but the response was not consistent. Whole-plant S concentrations at V5 were generally higher with all three materials than for the control (Table 2.). A tissue S concentration of 1.5 g/kg is considered adequate for maize at the V5 growth stage (Mills and Jones 1996). As predicted by the initial soil tests (Table 1), whole-plant P concentrations at V5 (Table 2) were within or above the sufficiency ranges. Nitrogen concentrations, however, were below the critical value 35 g/kg (Mills and Jones 1996). This suggests that the N applied with the S fertilizers plus residual soil N were not sufficient for maize growth before additional N was applied six weeks after planting. With respect to K, low tissue K concentrations (<25 g/kg) in 2007 presumably reflected low soil test K in four of the 16 plots.

At the mid-silk stage, ear leaf S concentrations (data not shown) were below the sufficiency range of 2.1 to 5.0 g/kg (Mills and Jones 1996), even when S was applied. The 3-year mean ear-leaf concentration for all treatments was 1.6 g/kg. During the 2006 and 2007 growing seasons, precipitation was below normal, and because soils supply S mainly via mass flow (Barber 1995), low concentrations of S in soil solution and low soil water content are suspected to have reduced the amount of S reaching the roots. In 2006 and 2007, maize yield and grain moisture content were not significantly affected by S fertilizer application (Table 3), even though 34 kg S/ha as SEF increased grain yield by 0.42 Mg/ha compared with the control. This difference was not significant ($p<0.05$) because of the variability among the plots, but with a less conservative level (p<0.10), the difference was significant. In 2007, 34 kg S/ha as either SEF or AMS increased grain yield by 0.63 Mg/ha compared with the control – a differences that was again significant at p<0.10 (Table 3). Again, below-normal precipitation during part of the 2006 and 2007 growing seasons and inherent soil variability at these locations likely affected the measured yield response to S fertilizer. In 2008, maize grain yield was increased 0.76 Mg/ha (p<0.05) with 34 kg S/ha as SEF (Table 3). Sulfur removal with harvested grain and plant residues (data not shown) was higher when S fertilizer was applied, suggesting that the maize took advantage of an increased S supply in 2008.

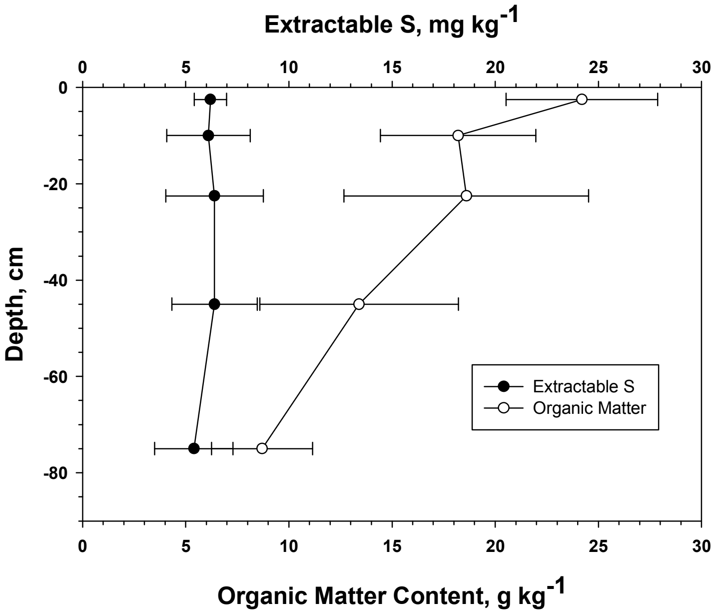

Figure 1. Extractable S and organic matter content in the soil profile of Clarion loam. Soil samples were collected to a depth of 1 m before planting in 2006. Bars indicate standard deviation of the mean of ten samples.

Agronomic efficiency of the three S sources was calculated to provide an index for grain produced per unit of applied S. In 2006 and 2008, SEF was clearly the most effective S source (Table 3). Although available P in the soils was sufficient for maize growth (Table 1), there may have been some beneficial effect of the additional P in the SEF material. In an experiment with ^{35}S-labelled fertilizer, Friesen (1996) found that P mixed with S increased maize growth and S recovery more than when P and S fertilizers were physically separated. The results were attributed to a P and N nutritional requirement of S-oxidizing microorganisms in the soil.

Table 2. Effect of 34 kg S/ha on whole-plant dry weight, and sulfur (S), nitrogen (N), phosphorus (P), and potassium (K) concentrations at the V5 growth stage of maize grown on three soils. Values are least square means of four replications. Values followed by the same letter are not significantly different at the 0.05 level.

Treatment	Dry Weight	Nutrient			
		S	N	P	K
	g/plant	------------------- g/kg --------------------			
2006 Field Trial					
Control	4.3b	1.7b	31.3b	4.7a	41.6a
13-33-0-15S (SEF)	7.4a	2.1a	34.3a	4.6a	35.1a
21-0-0-24S (AMS)	6.1ab	2.1a	34.9a	4.4a	38.1a
12-0-0-26S (ATS)	5.8ab	2.3a	31.8b	4.2b	39.2a
2007 Field Trial					
Control	6.0b	1.6b	28.9b	3.4a	20.1a
13-33-0-15S (SEF)	8.9a	2.0a	32.4ab	3.7a	17.1a
21-0-0-24S (AMS)	7.2ab	1.9a	32.7a	3.1a	18.5a
12-0-0-26S (ATS)	5.5b	1.8a	29.4ab	3.3a	18.1a
2008 Field Trial					
Control	5.4b	1.5b	24.0b	3.6a	37.3a
13-33-0-15S (SEF)	7.9a	1.7ab	26.4ab	3.9a	32.3a
21-0-0-24S (AMS)	6.6ab	1.9a	29.6a	3.3a	32.2a
12-0-0-26S (ATS)	7.0ab	1.8ab	25.0ab	3.2b	34.1a

Table 3. Effect of 34 kg S/ha on grain yields and grain moisture at harvest of maize grown on three soils. Values are least square means of four replications. Values followed by the same letter are not significantly different at the 0.05 level. Agronomic efficiency of S fertilizer sources is shown for comparative purposes.

Treatment	Grain Yield	Grain Moisture	Agronomic Efficiency
	Mg/ha	g/kg	kg grain (kg S)$^{-1}$
2006 Field Trial			
Control	10.65a	145a	-
13-33-0-15S (SEF)	11.07a	146a	12.3
21-0-0-24S (AMS)	10.76a	145a	3.3
12-0-0-26S (ATS)	10.72a	144a	2.1
2007 Field Trial			
Control	11.04a	149a	-
13-33-0-15S (SEF)	11.67a	146a	19.3
21-0-0-24S (AMS)	11.67a	147a	19.1
12-0-0-26S (ATS)	11.47a	146a	12.1
2008 Field Trial			
Control	12.05b	172a	-
13-33-0-15S (SEF)	12.81a	166a	22.5
21-0-0-24S (AMS)	12.05b	170a	0.1
12-0-0-26S (ATS)	12.18b	167a	4.1

Summary

Field trials were conducted to evaluate S fertilizer responses on eroded hill slopes in central Iowa, USA. Application of 34 kg S/ha as SEF increased V5 mean plant dry weight each year. Whole-plant S levels at V5 were generally higher for all S sources. In 2006 and 2007, maize grain yield was not increased and moisture content was not reduced by S application. In 2008, yield was increased 0.76 Mg/ha with SEF. Agronomic efficiency showed SEF to be the most effective S source. Below-normal precipitation during 2006 and 2007 growing seasons and inherent soil variability likely affected our S yield responses. These results suggest that S may become a limiting nutrient for Midwestern USA maize production, because surface soil on hill slopes is often eroded, common fertilizer materials contain less S as an impurity, and atmospheric deposition of S has decreased.

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