IS THERE AN OPTIMAL SOURCE OF SULFUR FOR CORN?

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ABSTRACT

Sulfur has become a common nutrient applied to corn in the Corn Belt. While research has demonstrated that sulfur can greatly increase yield, the source of sulfur offered to farmers by retailers can vary. Sulfur is only taken up by corn in the sulfate form while sulfur fertilizer source can contain sulfate that is readily available to plants or elemental sulfur which needs to be oxidized to sulfate before it is taken up by a crop. Four long-term research sites were established in Minnesota using a continuous corn rotation. Sulfur was applied at four rates (5, 10, and 20 lbs of S per acre) as four sources including a no-S control, sulfate-S applied as K-sulfate, elemental S as Tiger 90®, and elemental S as potash MST®. Treatments were applied and incorporated into the soil annually in the spring within 1 week of planting. Corn grain yield was significantly impacted by S application at three of the four locations. The only location where S did not increase yield was on a clay loam soil near Morris, MN that was heavy textured with soil organic matter concentration above 5%. For the remaining three sites, corn grain yield responded to sulfur rate (10 lbs S per acre) but not source at Becker, MN on an irrigated loamy sand soil. The remaining two locations corn grain yield responded to sulfur source and rate. For a silt loam soil near Rosemount, MN, 20 lbs of S per acre were needed to maximize yield across four years. In contrast for a clay loam soil at Waseca, MN, corn grain yield was maximized by 10 lbs of S per acre. The increase in sulfur requirement at Rosemount may be a result of a lower soil organic matter concentration (4% versus 6% at Waseca). At both locations, K sulfate and K-MST produced the greatest yield potential. Tiger 90 resulted in similar yield potential at Becker and Rosemount but yielded less at Waseca. It is possible that the Tiger 90 could not fully disperse the elemental S when incorporated into the soil and that coarser soils may help increase the potential for oxidation when a product like Tiger 90 is incorporated prior to planting. The data shows that sulfur application can be highly beneficial to corn, and that soil texture may play an important role in whether incorporated elemental S can oxidize to plant available forms.

INTRODUCTION

The response of corn grain yield to sulfur fertilization has been one of the major factors for increased productivity and profitability in some cropping rotations. Current projects on sulfur timing, rate, and placement have clearly demonstrated the need for sulfur. While a soil test is available for sulfur, differences in sulfate due to S application are difficult to detect with the soil test and soil test concentration of sulfate-S can be high even in soils where S responses occur. This highlights our limited understanding of how sulfur cycles among forms in the soil. Sulfate-S can be reduced in low oxygen situations but a complete reduction of sulfate to hydrogen sulfide which can be lost to the atmospheric via volatilization is unlikely. Basic research on forms of sulfur in the soil is needed to better understand availability in soils across Minnesota.

Elemental sulfur is a low-cost option for supplying S to plants but must be oxidized to sulfate prior to plant uptake. Oxidation is mediated by bacteria, *Thiobacillus thiobacteria*. From previous work, we know that the activity of *Thiobacillus* sp.tends to be low when soils remain cool. In fact, the optimum temperature for Thiobacillus activity is above 80^{o}F and even at these temperatures the oxidation of elemental sulfur can take 30 days. With more sources of S fertilizer containing elemental S due to a lower cost, research needs to identify whether any elemental S containing fertilizers can supply enough S for crops in situations where S is needed.

Research in Minnesota has demonstrated the need for sulfur to be applied to corn. However, the source of sulfur available to farmers can vary. The objective of this study is to compare sulfur release and availability of a sulfate source of S versus two sources of elemental S in a continuous corn rotation

MATERIALS AND METHODS

Table 1. Soil series information, planted crop at each location, and initial potassium soil test data from phosphorus studies conducted in 2019. Soil test data was collected in the Fall at trial establishment from each main plot.

	Soil Test				SO_4-S			
Location	Bray-P1	K	pH	OM	0-6	6-12	12-24	Soil Series
	ppm			%	ppm			
Becker	127	164	6.8	1.6	8.8	8.8	8.3	Hubbard
Morris	37	198	7.9	5.8	12.4	14.2	13.2	McIntosh
Rosemount	29	171	5.4	4.2	11.5	10.5	8.3	Tallula
Waseca	17	170	5.7	4.7	10.1	9.4	7.1	Clarion-Webster

† K, Soil test potassium (K-ammonium acetate); CCE, calcium carbonate equivalency.

Long term S research trials were established at four locations in 2019 (Table 1) Continuous corn trials were established at each location. Treatments were arranged in a split plot design. Main blocks consisted of 5, 10, or 20 lbs of S. Each main block was split into four sub-plots which were sulfur sources. Sulfur source treatments included a no sulfur control and three sources of S as potassium sulfate (0-0-50-17), Tiger 90 (60-800 micron elemental S and bentonite mixture), and a co-granulated S source. Co-granulated S materials, similar to what is contained in the micro-essentials line of products, are becoming more available and allow for a more even distribution of elemental S as each fertilizer granule contains S along with N and P unlike Tiger 90 which is 90% S therefore the amount of total product applied per acre is small reducing the distribution of sulfur over the landscape. The co-granulated product used for this study is a potash-based material consisting of 49% K_2O and 13.6% S manufactured by Sulvaris LTD (Calgary, AB) where the S is micronized to a smaller particle size (<40 microns). The use of a potash source eliminates the use of phosphate materials such as MAP, DAP, or TSP which can contain from 1-2% total S and can affect the ability to detect a response to S in a field study.

High P testing sites were selected, and additional P fertilizer was applied as a combination of in-furrow and 2x2 application of 6-24-6. Starter rate varied by site and typically were 5 gallons 6-24-6 in furrow at medium to fine textured sites plus 10 gallons 2x2. The in-furrow application rate was reduced to 3 GPA at Becker where the soil is a loamy sand. The 6-24-6 product was tested by ICP and averaged 667 mg S L^{-1}. Additional K as 0-0-60 will be applied to balance K across plots and N will be applied at non-limiting rates. Plots are 20' in width (except for Waseca which was 15' in width) , and were 40-55 feet in length. All sites were rain-fed except for Becker which was irrigated. The total irrigation applied at Becker in 2019 was 8.05 inches of water, 10.6 inches were applied in 2020, 14.3 inches in 2021, and 13.05 inches in 2022. Well water samples indicated an average of 29.8 mg SO4-S L^{-1} water at Becker in 2019, 31.0 in 2020, 27.1 in 2021, and 26.2 in 2022 which equates to 6.7, 7.0, 6.1, and 5.9 lb SO_4-S per inch of water applied, respectively. A total of 53.9, 74.3, 87.2, and 76.9 lbs SO_4-S was applied over 2019, 2020, 2021, and 2022 growing season through the irrigation water, respectively. The amount of S in rainfall was not determined at any of the locations.

Corn grain yield response (adjusted to 15.5% moisture) to S was measured in all plots. Corn leaf tissue samples were collected at V10 by sampling the uppermost fully developed leaf and at R1 sampling the ear leaf (leaf opposite and below the ear) and the 2nd leaf from the top of the plant. A subsample of grain will be saved from each plot, ground, and analyzed for total S concentration. All samples will be analyzed for total S concentration using combustion analysis. Soil test S will be measured from each main block at the beginning of the trial at the 0-6, 6-12, and 12-24" depth. Plant root simulator (PRS) probes, sold by Western Ag Innovations (Saskatoon, SK) were installed in the 10 lb S rate main blocks in all fertilizer sources and were sampled over a period of 8 sampling dates. A total of four anion probes were installed between the center two corn rows in an area 5' in each direction from the center of each plot. The PRS probes were installed in the soil to a depth of roughly 4-5 inches. At each sampling date the probes were removed from the soil, washed with deionized water, and new probes were re-installed into the slots created by the old probes. A garden knife was used to apply back pressure on the probes to ensure good contact between the soil and ion exchange membranes. Probes were sent to Western Ag. Innovations to be extracted and analyzed for sulfate-S sorbed. Soil samples (0-6 and 6-12") were collected prior to the initial PRS instillation and each time PRS probes are installed and removed. A total of three cores were sampled from between the rows where PRS probes were installed and were analyzed for sulfate-S using the mono-calcium phosphate procedure.

RESULTS AND DISCUSSION

Results of selected variable are summarized in Table 2. Corn grain yield was affected by sulfur sources at two of four locations while rate affected corn grain yield at three locations. Becker, the only irrigated location, saw corn grain yield increased by sulfur rate regardless of source. Sulfur source and rate both impacted corn grain yield at Rosemount and Waseca. At both these locations, K sulfate produced the greatest yield. The K-MST also produced maximum yield at both locations. However, Tiger 90 produced less yield at Waseca compared to K-sulfate and K-MST. Tiger 90 application did result in greater yield over the control, but the yield increase was only 60% that of K-sulfate and K-MST. What is interesting is that the sources, even the no-S control, did not affect grain yield at Becker even though statistically there was a difference between the 5 versus the 10 and 20 lb S application rates. There also was no significant interaction between source and rate at Becker. At Rosemount, 20 lbs of S was required to maximize corn grain yield over the 4 years while 10 lbs was sufficient at Waseca.

Table 2. Source and rate main effect means across four years 2019, 2020, 2021, and 2022 at four Minnesota locations. Within each main effect, within rows, numbers followed by the same letter are not significantly different at $P \leq 0.10$.

	Source Rate Effect				Rate Main Effect		
Location	Control	K-Sulfate	K-MST	Tiger 90	5	10	20
				Bushels per acre at 15.5% moisture			
Becker	197	200	196	197	189b	200a	202a
Morris	200	199	199	203	201	200	200
Rosemount	186b	207a	207a	201a	197b	195b	209a
Waseca	119c	177a	174a	153b	147b	158a	162a
				V10 Upper Leaf %S			
Becker	0.27b	0.29a	0.28ab	0.29a	0.28b	0.29a	0.29a
Morris	0.24	0.25	0.25	0.25	0.23b	0.25a	0.25a
Rosemount	0.20c	0.24a	0.24a	0.21b	0.21b	0.21b	0.24a
Waseca	0.17c	0.22a	0.22a	0.19b	0.19b	0.20b	0.21a
				R1 Ear Leaf %S			
Becker	0.26c	0.28a	0.27ab	0.27b	0.26b	0.27a	0.27a
Morris	0.23	0.23	0.23	0.22	0.22b	0.23ab	0.23a
Rosemount	0.18c	0.21a	0.21a	0.20b	0.19b	0.19b	0.21a
Waseca	0.14c	0.19a	0.18a	0.16b	0.16c	0.17b	0.18a
				R1 Upper Leaf %S			
Becker	0.25	0.25	0.25	0.24	0.24	0.25	0.25
Morris	0.23	0.23	0.22	0.23	0.22b	0.23a	0.23a
Rosemount	0.20d	0.24a	0.23b	0.21c	0.21b	0.21b	0.23a
Waseca	0.16c	0.21a	0.21a	0.18b	0.18c	0.19b	0.20c
				Grain %S			
Becker	0.095	0.096	0.097	0.099	0.096	0.098	0.096
Morris	0.094	0.096	0.096	0.096	0.095	0.095	0.096
Rosemount	0.088b	0.094a	0.093a	0.089b	0.089b	0.088b	0.096a
Waseca	0.070c	0.082a	0.081a	0.074b	0.072c	0.077b	0.082a

Corn leaf tissue and grain S concentration data are summarized in Table 2. Sulfur source and rate affected tissue S concentration more often than corn grain yield. Effects on leaf tissue S concentration were present even at Morris where corn grain yield was not impacted by S. Sulfur application rate almost always affected leaf tissue S concentration while source more commonly impacted leaf S concentration for the sites where grain yield were increased. Corn grain S concentration was only impacted by S source or rate at Rosemount and Waseca where both also impacted corn grain yield. Tissue S concentration was not regressed with yield to determine optimal leaf tissue S concentration. It is not surprising that S concentration was increased without an increase in corn grain yield occurring at a location as luxury uptake of S is expected by corn. It was surprising that leaf S concentration was impacted at Becker due to the large quantity of S contained in the irrigation water that was applied annually. Leaf S concentration did tend to be higher at Becker than the other locations. While not stated in the methodology, the same corn hybrid was planted across all locations each year so hybrid alone would not explain differences in leaf tissue S concentration.

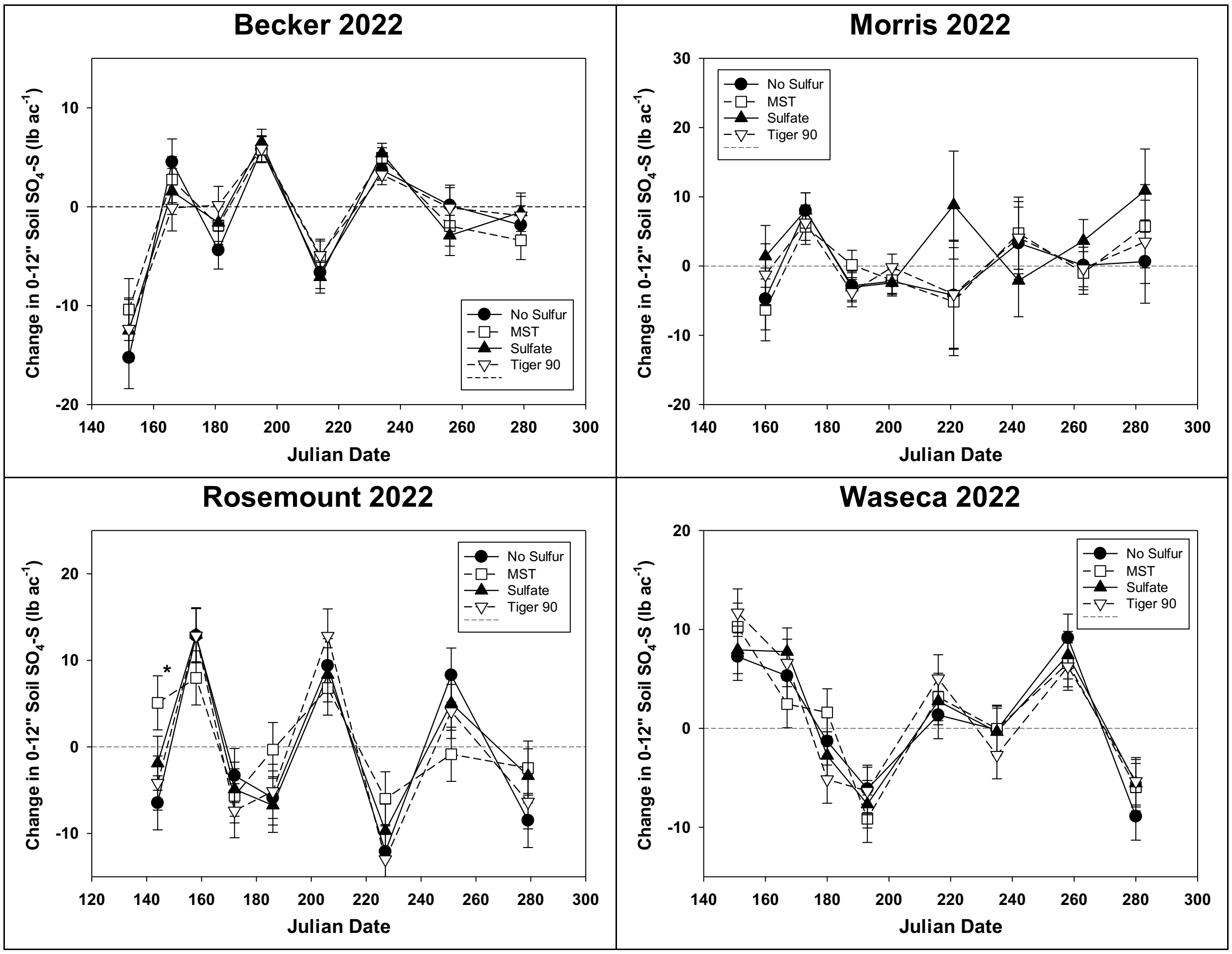

Figure 1. Summary of change in soil sulfate-S content at eight sampling dates from the initial soil sampling collected when the PRS probes were installed following the application of three sulfur sources at 10 lbs S/ac and a no-S control.

Plant root simulator (PRS) probes and soil samples were taken throughout the growing season in all four years of the study. Figures 1, 2, and 3 summarize only the 2022 results as the data were similar across years. Soil samples were collected from 0-6 and 6-12” depths when the PRS probes were installed and removed only in the main blocks receiving 10 lbs of S. Changes in the amount of S between samplings are summarized in Figure 1. Overall, there was no clear increasing or decreasing trend in the amount off extractable SO_4-S in soil measured to a 0-to-12-inch sampling depth. Increases or decreases were seen over time which could not be explained using soil temperature or moisture. The soil test for S is not that sensitive to applications of fertilizer and is not the best for indicating when S applied in fertilizer would become available as there was almost never a significant difference among the four sources at any individual sampling time.

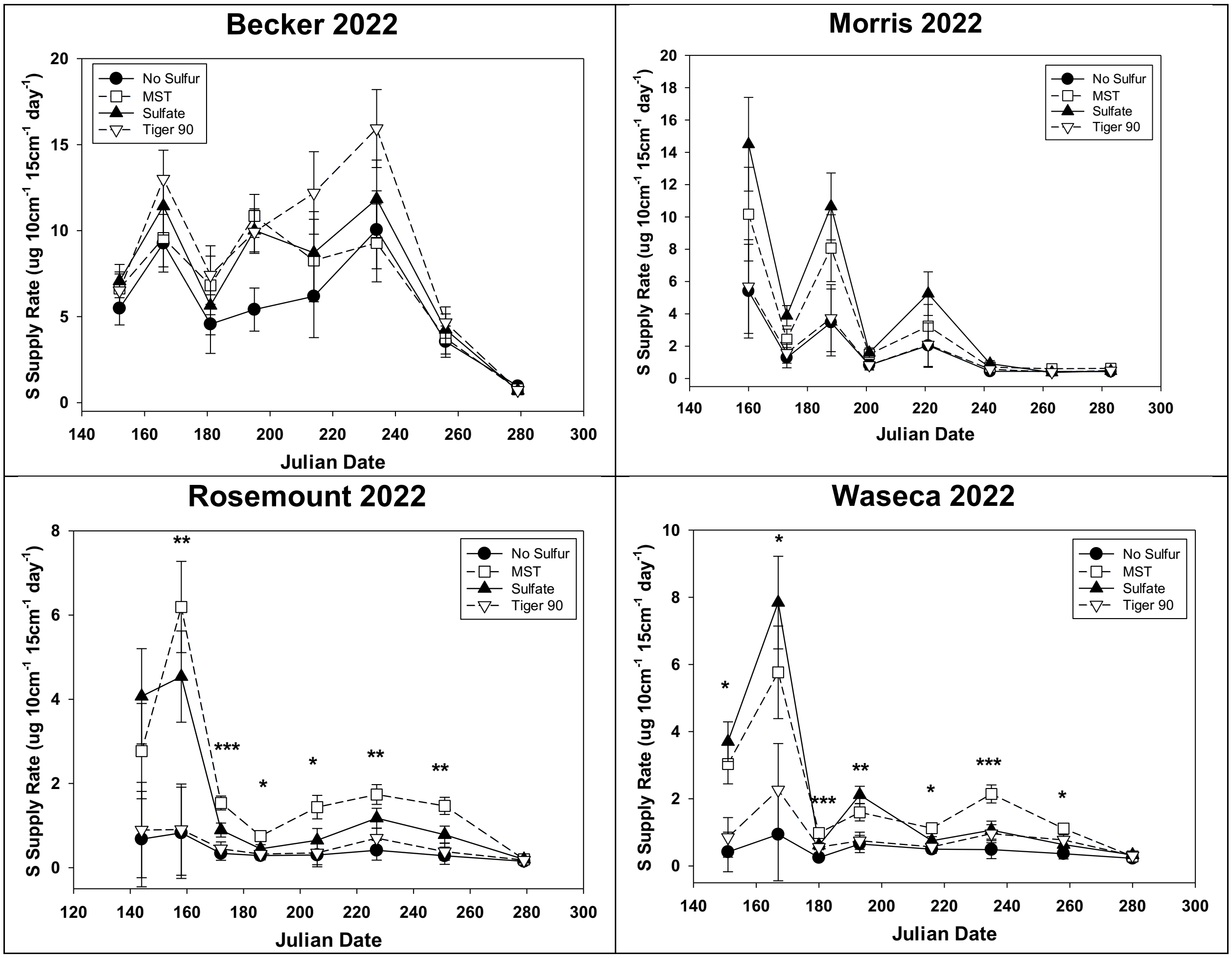

Figure 2. Summary of soil sulfate-S supply rate measured as daily sulfate-S flux by the PRS probes following application of three sulfur sources at 10 lbs S/ac and a no-S control.

Plant root simulator (PRS) probes were used as a proxy for plant roots to determine the amount of SO_4-S potentially available over time. The PRS data are summarized based on daily supply rate (Figure 2) as well as total SO_4-S sorbed over time (Figure 3). The units obtained from the PRS probes are presented in terms of a flux which is the amount of SO_4-S sorbed per unit surface area per unit time. The data are not intended to determine the total amount of sulfate released from the fertilizer. Rather we are interested to know when the different fertilizer sources may be providing available S to the plant. Asterisks in Figures 2 and 3 denote instances where where was variation among the sources at each site. Differences in daily sulfate flux could only be measured at Rosemount and Waseca in 2022. The availability of S from K-sulfate could be seen at the initial sampling and dropped off considerably by the third sampling at each location. Initial availability of S from K-MST was lower than K-sulfate for the first one or two samplings, but available S tended to be greater with K-MST compared to K-sulfate for the mid- to late sampling dates. Tiger 90 did not exhibit any significant availability of S over the growing season compared to the other two sources. However, Tiger 90 did increase corn grain yield at both Rosemount and Waseca therefore the PRS data wasn't fully reflective of the amount of S becoming available to the crop.

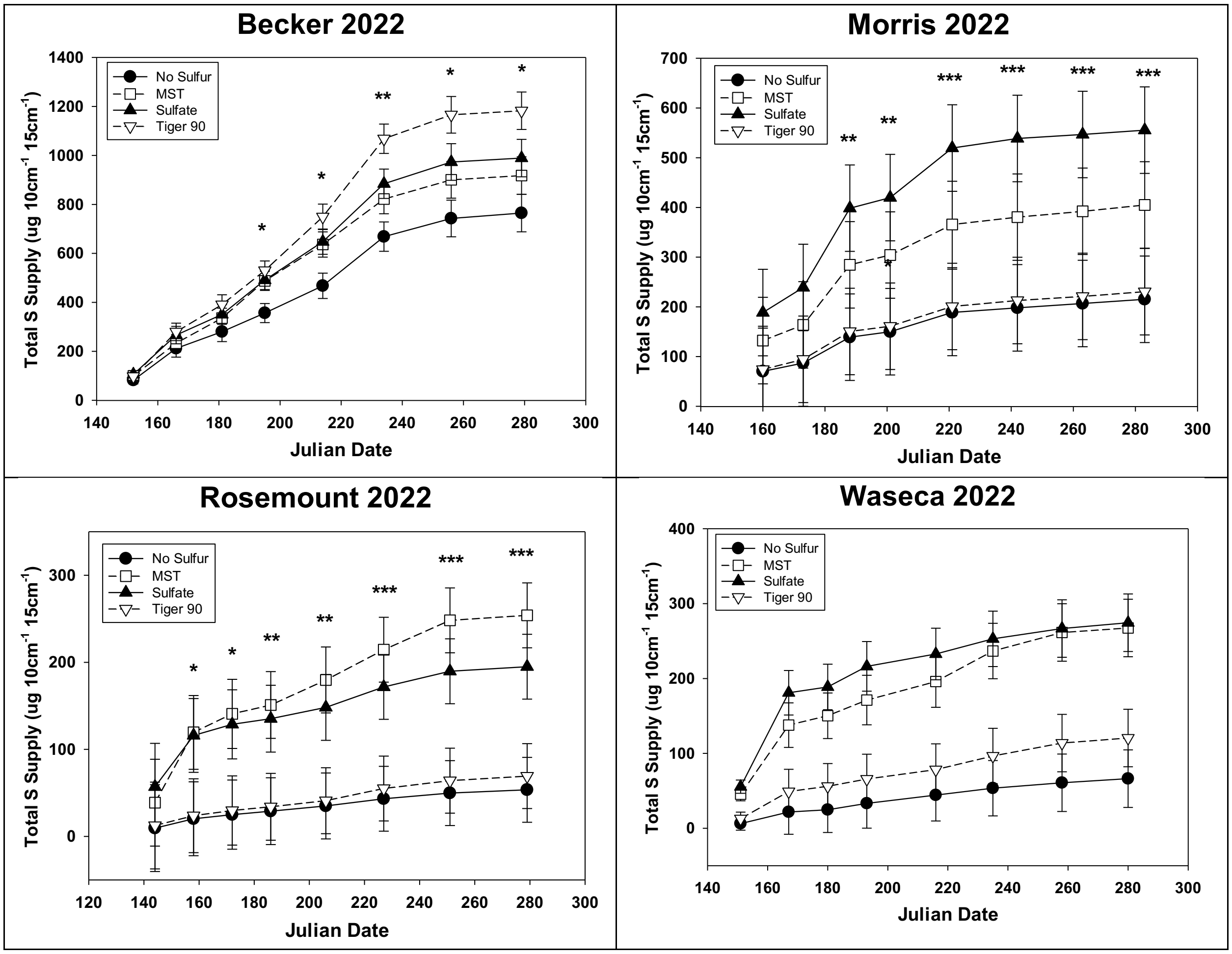

Figure 3. Summary of cumulative sulfate-S adsorption by the PRS probes following application of three sulfur sources at 10 lbs S/ac and a no-S control.

The total S supply shown in Figure 3 shows more difference in S availability from the individual sources across the four locations compared to the daily flux data shown in Figure 2. In fact, total S supply varied among S sources at all four locations. Asterisks are not presented for Waseca in Figure 3. However, that was due to no source by sampling date interaction. In fact, the total S supply data matched better with corn grain yield at Waseca where K-sulfate and K-MST yielded more than Tiger 90. One thing to note is that for Becker and Morris the scale on the Y axis is much larger than the other two locations indicating a generally larger supply of sulfur coming from the soil due to organic matter mineralization at Morris, and through the contribution of sulfate in the irrigation water at Becker. Even though the sources did vary, the additional supply of S by S fertilizer at Becker and Morris was not likely needed. Again, Becker did respond to rate but not to source. At Rosemount, the K-MST did supply more total sulfur over time than K sulfate.

The PRS data does give some indication of when S is becoming available for the crop. In the case of K-MST, available S is lower than K-sulfate initially, but the K-MST appears to supply more S at mid- to late growth stages. Across the four years, the elemental S in K-MST seemed to start to become more available about four to six weeks into the growing season. What is interesting though is that the Tiger 90 did not show to be any more affective compared to the no S control at Rosemount even though statistically is provided the same yield at the end of the season. The only site were Tiger 90 appeared to be better at supplying S was at Becker where the total S supply was greatest with Tiger 90 at the end of the 2022 growing season.

The fact that the Tiger 90 did not produce similar yield compared to K-sulfate and K-MST is not surprising for Waseca. The larger particle size of the elemental sulfur combined with the bentonite likely slows the oxidation in soils such as Waseca and Morris that are high in clay. Elemental sulfur is not water soluble and burying large particles in the soil would slow oxidation. Also, the bentonite clay in the Tiger 90 would not be able to disperse the elemental S if buried in soils with smaller pore spaces. The potash matrix in the K-MST would likely dissolve leaving more space for the elemental S in the K-MST to avoid all the elemental S clumping together which would increase the overall diameter of S particles and slow oxidation. Coarse textured soils such as that at Becker would leave more space for the bentonite to expand and potentially disperse the elemental S particles.

CONCLUSIONS

The data provided indicates that elemental S can be an effective source of S fertilizers for crops. Elemental S needs to be managed differently than other S sources. Co-granulated materials such as the K-MST may have a greater chance of supplying available S to crops due to a smaller particle size and better dispersion of the sulfur across the landscape. For fine textured soils, a project like Tiger 90 is not as effective when incorporated into the soil and the rate of S needed to result in maximum yield may be at least two times greater than that which would be required using a sulfate source of fertilizer. The data does indicate that no more than 20 lbs of S are required annually for corn grown in a continuous corn cropping system which optimal rates as low as 10 lbs of S per acre in some circumstances.

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