Understanding mechanisms of sulfur cycling in Minnesota soils and availability from fertilizer

AFREC Project Report 03/31/2024 for

AFREC Project(s) R2023-D Year 5 Report

Crop Year - 2023

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Year 5 (2023) Summary Points

- Sulfur increased corn grain yield at two locations. Application of 10-20 lbs of S per acre was sufficient for medium to fine textured soils.
- Sulfur was carried over from the previous 4 years' application. MST provided the greatest potential for sulfur carryover.
- Tiger 90 appeared to benefit corn from the previous years' sulfur application. However, Tiger 90 still appeared to result in less available S than sulfate or MST.
- Sulfate forms of sulfur and MST generated the highest grain yield with annual fertilizer application.

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 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 tends to be low when soils remain cool. In fact, the optimum temperature for Thiobacillus activity is above 80oF and even at these temperatures the oxidation of elemental sulfur can take 30 days. Developing an accurate model of oxidation is important to understand how to effectively utilize elemental sulfur in cropping systems. In addition, long-term studies where elemental sulfur sources are compared to sulfate are needed to assess whether oxidation later in the growing season can lead to a buildup of sulfate which, over time, will supply enough available sulfate sulfur to a crop.

Phase II of the proposed field study will continue to compare multiple rates of S as sulfate and elemental S products. Fertilizer application will be terminated on half of the previously used plots at two of the four locations where differences among fertilizer sources occurred to better understand the longevity of sulfur treatments for increasing corn S concentration on grain yield.

<u>Objectives</u>

1. Compare sulfur release and availability of a sulfate source of S versus two sources of elemental S in a continuous corn rotation.
2. Evaluate the ability of S concentration in plant tissue to predict corn grain yield.
3. Determine whether available sulfur is released from elemental S for one or more years following application.

Materials and Methods:

This proposal includes a continuation of the two of the four trial locations established for the 2019 growing season at Rosemount, and Waseca. These locations will be continued as corn grain yield was impacted by sulfur sources. There was no response to sulfur at Morris while Becker there was a response to sulfur rate but no variation among the sources. Plots at Rosemount and Waseca were established such that they could be sub-divided for phase two and treatments could be continued on half the plot and discontinued on the other half to study how long effects of sulfur applied over four growing seasons carries over to following years.

Treatments are a no sulfur control and three sources of S (potassium sulfate, Tiger 90, and potassium MST from Sulvaris Inc. out of Canada). Fertilizer P will be applied as 6-24-6 liquid fertilizer in a band with the planter (combination of 2x2 and in-furrow application). All sulfur products will be applied to supply 5, 10, and 20 lbs of S per acre annually and treatments will be re-applied to each plot every year. Plots established will be 20' in width or longer in length to allow for sub-dividing for Phase II to focus on draw-down of sulfur the soil (2023 growing season). All treatments will be replicated four times at each location and all fertilizer will be applied in spring.

To reduce costs, I am proposing a significant reduction in the number of plant samples collected. Leaf samples will be collected at V10 (upper leaf) and R1 ear leaf only. Corn grain yield will be measured in all plots and grain subsamples will be collected and used for assessment of yield parameters (seed weight) and S removal in grain.

Soil test S will be measured from each plot every fall at the 0-24" depth. The plant root simulator probes will not be used for phase 2 and the XANES work will be discontinued as well.

Table 1. Soil series information, planted crop at each location, and initial potassium soil test data from phosphorus studies when established in spring of 2019.

	Soil Test				SO_4-S			
Location	Bray-P1	K	pH	OM	0-6	6-12	12-24	Soil Series
	ppm			%	ppm			
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.

Table 2. Summary of cultural practices for studies conducted from 2019 to 2023. Soil test data was collected in the Fall at trial establishment from each main plot.

			Date of		
Year	Location	Cultivar†	Spring Fert.	Planting	Harvest
2019	Becker	DK 50-08	3-May	4-May	24-Oct
	Morris	DK 50-08	14-May	15-May	14-Nov
	Rosemount	DK 50-08	7-May	16-May	28-Oct
	Waseca	DK 50-08	15-May	16-May	24-Oct
2020	Becker	DK 51-38	6-May	6-May	15-Oct
	Morris	DK 51-38	11-May	11-May	26-Oct
	Rosemount	DK 51-38	1-May	12-May	13-Oct
	Waseca	DK 51-38	4-May	7-May	15-Oct
2021	Becker	DK 49-44	7-May	7-May	25-Oct
	Morris	DK 49-44	12-May	12-May	3-Nov
	Rosemount	DK 49-44	10-May	10-May	14-Oct
	Waseca	DK 49-44	10-May	10-May	2-Nov
2022	Becker	DK 49-44	15-May	16-May	28-Oct
	Morris	DK 49-44	25-May	26-May	20-Oct
	Rosemount	DK 49-44	6-May	10-May	27-Oct
	Waseca	DK 49-44	16-May	16-May	13-Oct
2023	Rosemount	DK 101-33	2-May	16-May	7-Nov
	Waseca	DK 101-33	28-Apr	22-May	23-Oct

† Dk, Dekalb.

Table 2. ANOVA summary of treatment main effects and their interactions for selected variable measured at the two field locations in 2023. Main effects consisted of sulfur application rate (Ra), sulfur source (So), and residual versus direct application of sulfur (App).

Main Effect	V5 NDRE	V10 Leaf S	V10 SPAD	R1 Leaf S	R1 SPAD	Yield	Grain S	Fall SO_4-S
				-----------------*P*>F-----------------				
				Rosemount				
S rate	*	**	0.23	*		0.10	***	0.24
S Source	***	***	***	***		0.11	***	0.56
Rt.xSource	0.88	0.13	0.14	0.12		0.43	0.17	0.28
App	*	***	*	***		0.14	***	0.56
Rate*App	0.07	0.80	0.46	0.59		0.92	0.33	0.87
Source*App	**	**	*	***		0.63	**	0.35
RaxSoxApp	0.14	0.81	0.48	0.54		0.96	0.21	0.34
				Waseca				
S rate	0.09	***	**	*	*	***	***	0.66
S Source	***	***	***	*	0.41	***	*	0.53
Rt.xSource	0.70	***	0.29	0.60	0.11	0.12	0.22	0.68
App	***	0.07	**	0.11	0.64	**	*	0.68
Rate*App	0.80	0.51	*	0.89	0.55	0.19	0.22	0.17
Source*App	**	0.07	***	0.12	0.71	*	0.10	0.09
RaxSoxApp	0.26	0.28	0.60	0.92	0.76	0.35	0.15	0.99

Asterisks denote significance at $P \leq 0.001$ (***), $P \leq 0.01$ (**), and $P \leq 0.05$ (*) probability levels.

Results and Discussion

Location Characteristics

Table 1 summarizes soil series information and soil chemical properties for the four locations. The two locations utilized for Phase II were those that previously showed response among the various sulfur sources. Becker and Morris were not continued as, of the two, only Becker showed a response to any variable which was sulfur rate. The primary need of Phase II was to study the impact of drawdown of sulfur over time which required sources response to S. None of the locations used for Phase II were irrigated.

Early and mid-season sensing and tissue S concentration

A summary table for the ANOVA for all measured variables is given in Table 2. Individual discussions will not be included for all in-season plant tissue measurements at treatment significance was similar for V5, V10, and R1 tissue measurements. It should be noted that the SPAD data at R1 was not collected at Rosemount due to leaf damage from a hail event in July. There was enough leaf tissue present to collect the leaf samples themselves at R1 at Rosemount. The V5 through R1 data are presented in Tables 3 through 7.

In most cases the sulfur source and rate main effects were significant along with the residual versus direct application main effect. More importantly the source by application time effect interaction was significant for most of the variables. Highest values were generally achieved with the direct application of sulfate or MST. The residual MST effect generally also produced maximum values for the measured variables while values tended to be lower for the residual sulfate application plots. Tiger 90 was generally better than the control, but the annual Tiger 90 application did not produce values greater than annual sulfate or MST and generally the annual Tiger 90 application was no different than the residual. The fact that there was no difference whether Tiger 90 was directly or indirectly applied may indicate a bulk of any impact from the Tiger 90 is coming from residual impacts from fertilizer applied previous years. The general positive benefit of the residual MST would also indicate a greater long-term benefit of elemental S as MST compared to Tiger 90.

What was surprising was the lack of interaction between application timing and rate. I would expect that the lower application rates of S would not supply adequate sulfur, but higher rates may provide some carryover benefit from the standpoint of excess sulfur application leaving some residual S for the following years. The S rate by application time interaction was only significant at Waseca for the V10 SPAD readings and the three-way interaction with source, rate, and application time was never significant. The three-way interaction may become more significant over time as sulfate-S is depleted from the soil.

Table 3. Summary of early plant vigor measured at the normalized difference red-edge (NDRE) data collected with a Crop Circle 430 active sensor collected at the V5 growth stage.

S	Control		K_2SO_4		K-MST		Tiger 90		
Rate	Annual	Resid.	Annual	Resid.	Annual	Resid.	Annual	Resid.	Avg
lb									
					Rosemount				
5	0.18	0.19	0.22	0.21	0.23	0.23	0.21	0.21	0.21b
10	0.20	0.18	0.25	0.22	0.23	0.22	0.21	0.22	0.22b
20	0.21	0.20	0.26	0.24	0.26	0.26	0.23	0.25	0.24a
Avg	0.20d	0.19d	0.25a	0.23bc	0.24ab	0.24ab	0.22c	0.23bc	
Avg	0.19c		0.23ab		0.24a		0.22b		
					Waseca				
5	0.22	0.22	0.26	0.23	0.26	0.26	0.26	0.26	0.25b
10	0.24	0.23	0.27	0.25	0.27	0.26	0.27	0.27	0.26a
20	0.23	0.23	0.27	0.25	0.28	0.27	0.28	0.27	0.26a
Avg	0.23c	0.23c	0.26a	0.24b	0.27a	0.27a	0.27a	0.26a	
Avg	0.23c		0.25d		0.27a		0.27a		

Table 4. Summary of leaf S concentration measured from the uppermost fully developed corn leaf at the V10 growth stage at four Minnesota locations during the 2023 growing season.

S	Control		K_2SO_4		K-MST		Tiger 90		
Rate	Annual	Resid.	Annual	Resid.	Annual	Resid.	Annual	Resid.	Avg
lb			---------------V10 Upper Leaf %S---------------						
					Rosemount				
5	0.22	0.21	0.27	0.23	0.27	0.25	0.24	0.23	0.24c
10	0.23	0.22	0.28	0.25	0.30	0.28	0.26	0.25	0.26b
20	0.23	0.22	0.29	0.27	0.32	0.30	0.28	0.27	0.27a
Avg	0.22e	0.22e	0.28ab	0.25d	0.30a	0.28bc	0.26cd	0.25d	
Avg	0.22c		0.26b		0.29a		0.25b		
					Waseca				
5	0.19	0.18	0.22	0.20	0.22	0.22	0.22	0.20	0.21c
10	0.17	0.19	0.22	0.21	0.25	0.25	0.22	0.22	0.22b
20	0.19	0.18	0.28	0.24	0.28	0.26	0.24	0.26	0.24a
Avg	0.18d	0.18d	0.24ab	0.22c	0.25a	0.25a	0.23bc	0.23bc	
Avg	0.18c		0.23b		0.25a		0.23b		

Table 5. Summary of SPAD meter reading collected from the middle of the uppermost fully developed corn leaf at the V10 growth stage at four Minnesota locations during the 2023 growing season.

S	Control		K_2SO_4		K-MST		Tiger 90		
Rate	Annual	Resid.	Annual	Resid.	Annual	Resid.	Annual	Resid.	Avg
lb									
					Rosemount				
5	49.4	49.2	56.2	53.9	55.7	54.1	52.5	54.0	53.1b
10	50.4	49.4	56.2	53.1	56.2	55.9	54.2	53.9	53.6ab
20	52.2	50.6	56.1	55.5	54.9	54.8	55.0	56.3	54.4a
Avg	50.6c	49.7c	56.1a	54.2b	55.6ab	54.9ab	53.9b	54.8ab	
Avg	50.1b		55.2a		55.3a		54.3a		
					Waseca				
5	43.4	43.3	50.3	45.6	50.5	48.5	48.9	47.0	47.2b
10	43.0	44.5	49.7	47.7	50.4	51.4	49.6	47.7	48.0b
20	42.9	43.9	54.1	51.2	52.0	51.5	51.0	51.3	49.7a
Avg	43.1d	43.9d	51.3a	48.1c	51.0a	50.4ab	49.9abc	48.7bc	
Avg									

Table 6. Summary of leaf S concentration measured from the corn leaf opposite and below the ear at the R1 growth stage at four Minnesota locations during the 2023 growing season.

S	Control		K_2SO_4		K-MST		Tiger 90		
Rate	Annual	Resid.	Annual	Resid.	Annual	Resid.	Annual	Resid.	Avg
lb					---------------R1 Ear Leaf %S---------------				
					Rosemount				
5	0.16	0.16	0.21	0.18	0.21	0.19	0.18	0.18	0.19b
10	0.14	0.15	0.22	0.19	0.24	0.21	0.19	0.18	0.19b
20	0.18	0.17	0.26	0.23	0.25	0.24	0.22	0.23	0.22a
Avg	0.16d	0.16d	0.23a	0.20c	0.23a	0.21b	0.20c	0.20c	
Avg	0.16c		0.21a		0.22a		0.20b		
					Waseca				
5	0.14	0.12	0.17	0.15	0.18	0.17	0.17	0.17	0.16b
10	0.14	0.14	0.19	0.17	0.19	0.17	0.17	0.17	0.17b
20	0.14	0.15	0.21	0.18	0.22	0.22	0.20	0.21	0.19a
Avg	0.14	0.14	0.19	0.17	0.19	0.19	0.18	0.18	
Avg	0.14b		0.18a		0.19a		0.18a		

Table 7. Summary of SPAD meter reading collected from the middle of the leaf opposite and below the ear at the R1 growth stage at four Minnesota locations during the 2023 growing season.

S	Control		K_2SO_4		K-MST		Tiger 90		
Rate	Annual	Resid.	Annual	Resid.	Annual	Resid.	Annual	Resid.	Avg
lb									
					Rosemount				
5									
10									
20									
Avg									
Avg									
					Waseca				
5	51.9	49.8	51.4	49.7	50.7	50.2	48.8	48.7	50.1b
10	46.7	48.4	49.4	49.2	51.7	51.9	50.4	50.1	49.7b
20	48.8	51.3	51.3	50.8	52.1	52.3	53.4	51.2	51.4a
Avg	49.1	49.8	50.7	49.9	51.5	51.5	50.9	50.0	
Avg	49.5		50.3		51.5		50.4		

Table 8. Summary of corn grain yield response to S source and rate at four Minnesota locations during the 2023 growing season.

S	Control		K_2SO_4		K-MST		Tiger 90		
Rate	Annual	Resid.	Annual	Resid.	Annual	Resid.	Annual	Resid.	Avg
lb	--------Corn Grain Yield at 15.5% Moisture (bu/ac)--------								
					Rosemount				
5	186	187	202	197	213	203	194	197	197ab
10	181	175	210	198	189	188	201	202	193b
20	201	194	211	201	220	218	217	215	210a
Avg	189	185	208	198	207	203	204	205	
Avg	187b		203a		205a		204a		
					Waseca				
5	120	105	183	138	199	187	167	170	159b
10	133	133	200	179	200	194	189	187	177a
20	124	114	203	195	200	213	208	200	181a
Avg	126c	117c	196a	171b	199a	198a	186ab	185ab	
Avg	121c		183b		199a		187ab		

Corn grain yield data are summarized in Table 8. As expected, both locations responded to sulfur in 2023. The average yield was lower than expected though due to dry weather conditions at both locations (not shown). Source and rate main effects were significant at both locations. At Rosemount all sources increased yield similarly while the MST treatments outyielded both sulfate and Tiger 90 at Waseca. The MST did better at Waseca thought due to lower yield with the residual sulfate compared to annual sulfate application at Waseca. In fact, the residual sulfate treatments yielded only slightly better than the control an slightly less than Tiger 90. Similar to tissue measures, corn grain yield was not impacted by the three-way interaction or was there no interaction between S rate and application timing in spite of lower yield for the sulfate residual treatment were only 5 lbs of S was applied annually. The lack of the three-way interaction is likely due to little difference between residual and annual treatments for most sources and rates during year 1 of the study. Over time I would expect to see more differences emerge similar to expectations for early plant tissue measures as the sulfur starts to delete in the soil over time.

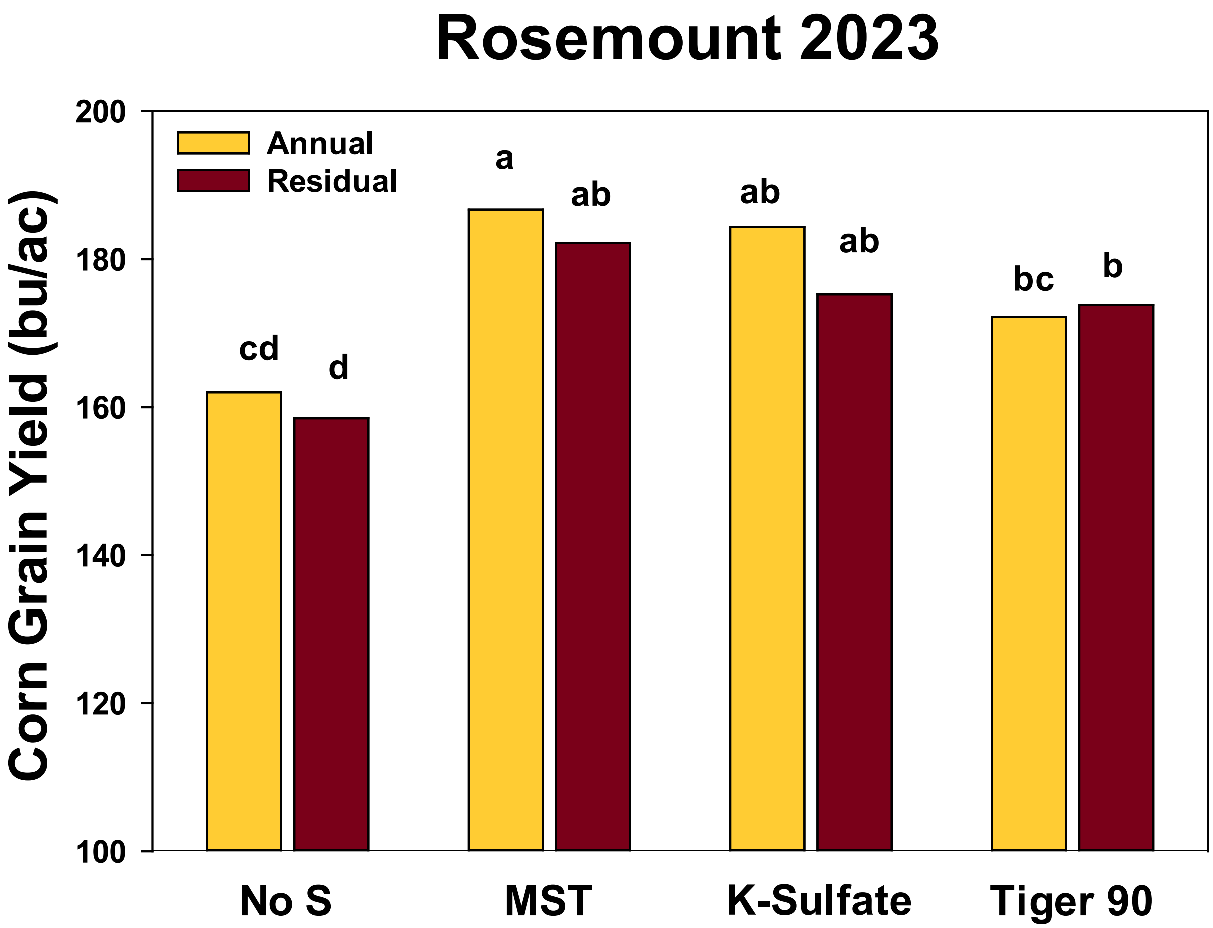

Figure 1. Summary of the interaction between sulfur source and application timing on corn grain yield at Rosemount in 2023. Small letters represent treatment significance at $P \leq 0.10$.

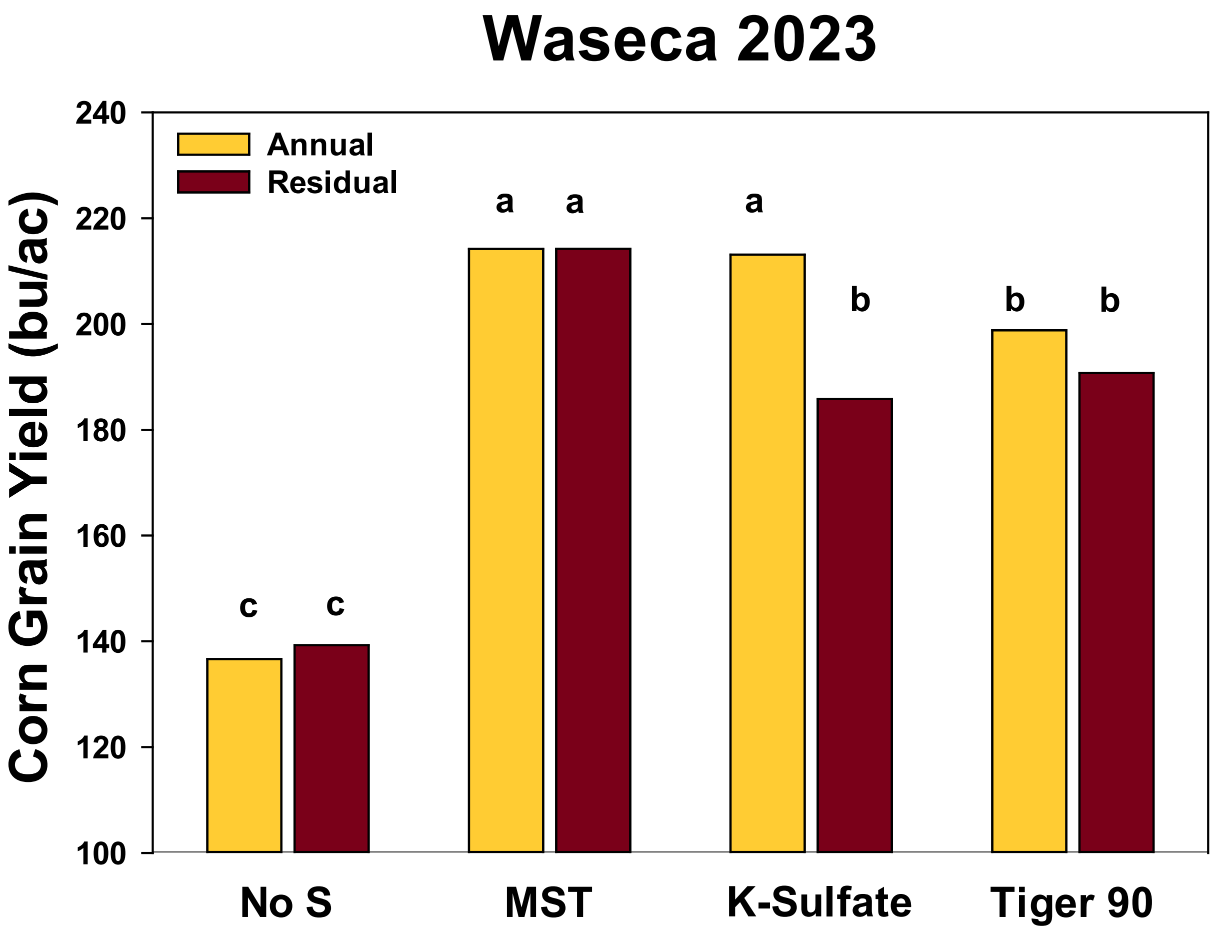

Figure 2. Summary of the interaction between sulfur source and application timing on corn grain yield at Waseca in 2023. Small letters represent treatment significance at $P \leq 0.10$./

The two-way source by timing interaction is summarized for Rosemount and Waseca in Figures 1 and 2, respectively. The highest yields were typically achieved by annual applications of sulfate or MST. However, the residual MST tended to produce similar yield compared to annual application at both locations. The residual sulfate treatments did produce slightly less yield which was expected as sulfate-S would be at greatest risk for leaching loss and would not be expected to remain in the soil for the lower annual application rates over time. Similar to early plant tissue impacts, corn grain yield with Tiger 90 was less than the other two sources and there was little to no difference when Tiger 90 was applied. This again might indicate that the relative impact of Tiger 90 on yield comes from previous application and not the application made for the current crop. It should be noted that the Tiger 90 was incorporated which could result in lower availability. However, does appear to stick around longer and possibly provide a longer-term source of sulfur for corn. These trials are planned to continue to see how long the effects may last over time. I would suspect that the low rate of MST may start to yield significantly less in plots where the residual impacts are being measured.

Table 9. Summary of corn grain S concentration response to S source and rate at four Minnesota locations during the 2023 growing season.

S	Control		K_2SO_4		K-MST		Tiger 90		
Rate	Annual	Resid.	Annual	Resid.	Annual	Resid.	Annual	Resid.	Avg
lb	---------------Corn Grain %S Concentration---------------								
	Rosemount								
5	0.07	0.07	0.08	0.08	0.09	0.08	0.07	0.07	0.07c
10	0.07	0.07	0.09	0.08	0.09	0.08	0.08	0.08	0.08b
20	0.07	0.07	0.11	0.10	0.10	0.10	0.10	0.10	0.09a
Avg	0.07c	0.07c	0.10a	0.09b	0.10a	0.09b	0.08b	0.08b	
Avg	0.07c		0.09a		0.09a		0.08b		
	Waseca								
5	0.08	0.07	0.09	0.08	0.09	0.08	0.09	0.08	0.08c
10	0.08	0.08	0.10	0.09	0.10	0.10	0.09	0.10	0.09b
20	0.09	0.08	0.12	0.10	0.11	0.11	0.10	0.11	0.10a
Avg	0.08	0.08	0.10	0.09	0.10	0.10	0.10	0.10	
Avg	0.08b		0.10a		0.10a		0.09a		

Table 9 summarizes the concentration of S in the harvested grain. Main treatment effects were similar for grain S concentration compared to other results with significant S rate and source main effects at both locations. The source by timing interaction was only significant at Rosemount though and similar to other results the highest grain S concentrations were achieved with annual application of sulfate and MST.

Soil sulfate-S content was measured post-harvest and was not affected by sulfur source or rate at any locations (Table 10).

Table 10. Summary of post-harvest two-foot soil extractable sulfate-S response to S source and rate at four Minnesota locations during the 2023 growing season.

S	Control		K_2SO_4		K-MST		Tiger 90		
Rate	Annual	Resid.	Annual	Resid.	Annual	Resid.	Annual	Resid.	Avg
lb	---------------Fall 2’ Soil Sulfate-S (lb/ac)---------------								
	Rosemount								
5	113	123	116	114	110	100	101	105	110
10	92	107	105	103	107	97	113	98	103
20	107	102	122	116	107	118	123	114	114
Avg	104	111	114	111	108	105	113	105	
Avg	107		113		107		113		
	Waseca								
5	108	97	92	100	93	103	103	105	100
10	103	98	93	102	102	115	98	98	101
20	130	98	102	102	105	102	104	96	105
Avg	113	97	95	101	100	106	102	100	
Avg	105		98		103		101		