Proceedings of the Integrated Crop Management Conference
Proceedings of the 24th Annual Integrated Crop Management Conference

Nov 28th, 12:00 AM

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Introduction

With input and crop prices significantly fluctuating in the last few years soybean growers have been looking for ways to maximize profits per acre. Sulfur application has been increasingly questioned as a method at increasing corn yields across southern Minnesota. However, past research has not shown a positive yield benefit for sulfur applied to corn unless the soils are sandy with low organic matter (Rehm, 2005) and most research has found that soil tests for sulfur do not work in fine textured soils. Currently, 25 lbs of sulfur per acre is recommended for corn when grown on coarse textured low organic matter soils (Rehm et al., 2006). If producers are banding sulfur then recommended rates are cut to 12 to 15 lbs. For many producers band application takes place in the form of starter fertilizer (small amount of fertilizer applied with the seed at planting). In Minnesota ammonium polyphosphate [APP (10-34-0)] is a popular choice for many producers as a starter fertilizer. However, many are tempted to mix sulfur containing products with APP in order to boost yields which is risky since this is not a recommended practice due to concerns with stand loss from the seed applied fertilizer (Rehm et al., 2006). Since many producers apply their dry fertilizers in the fall there are concerns with the loss of sulfate sulfur in the early spring through leaching and not adding yield to the next year's crop.

Over the past five to ten years yellow areas attributed to nitrogen deficiency in fields have developed that have not responded to additional applications of nitrogen fertilizer. Additionally, work in Northeast Iowa has shown that sulfur deficiencies are possible in fine textured soils (Sawyer and Barker, 2002; Sawyer et. al., 2009) that were eroded or had low organic matter content. Other research in southern Minnesota has noted occasional crop responses in areas where none were expected in the past (Randall and Vetsch, unpublished data). Many fields in Southcentral and Southeastern Minnesota have a rolling topography. In many of these fields yellowing can be visually noted throughout the growing season which could be a symptom of either sulfur or nitrogen deficiency. The question is can a specific nutrient deficiency be separated out in these areas and what kind of variability in the response to nutrient can be expected across a landscape.

A replicated strip trial study was conducted at multiple southern Minnesota locations with the following objectives:

1. Examine how different soils in a landscape may respond to sulfur fertilization
2. Evaluate how the application of nitrogen and phosphorus fertilizers mixed with sulfur may affect plant growth and the overall uptake and response from sulfur fertilization

Experimental methods

Four corn trials were established in 2008 and 2009 (Table 1). A replicated strip trial methodology was used at each location. Fertilizer strips measuring 10 to 20 feet (4 to 8 30 inch corn rows) wide and 520 to 880 feet long were established parallel to the direction of the corn rows in which six treatments were applied, randomized, and were replicated three to four times at each location. Treatments were a control with no starter or sulfur fertilizer, broadcast sulfur applied at 25 lbs S per acre and four starter fertilizer mixes were applied as field length strips. The starter fertilizer treatments consisted of 20 lbs of N/acre, 20 lbs of P_2O_5/ac, and 25 lbs of S/acre applied in combinations of N only, N+P, N+S, and N+P+S. Liquid fertilizer treatments were applied two inches beside and below the seed with a John Deere 7000 series planter equipped to simultaneously apply 28% UAN, ammonium polyphosphate (10-34-0), and ammonium thiosulfate (12-0-0-26s) to achieve the targeted starter rates. Dry potassium sulfate (0-0-50-18s) was used as the broadcast sulfur source and potassium chloride (0-0-60) was applied at high enough rates to limit crop response to strips not receiving potassium sulfate (potassium application rate was identical across the trial areas). Additional nitrogen and phosphorus fertilizer and lime were applied according to recommended rates by the farmer.

Within each rep across treatment strips the field areas were segmented into 120 foot increments for soil sampling. These increments represented grid cells within the trial area measuring 60 to 120 feet wide and 120 feet long

(0.17 to 0.34 acres). Soil samples were collected from the 0-6, 6-12, and 12-24 inch depths from the center of each grid cell. Each sample consisted of a composite of 6 to 8 cores taken from each cell. Soil samples were analyzed for Bray-P1 phosphorus, ammonium acetate potassium, soil organic matter, and pH (Table 1) by methods recommended in the North-central region (Brown, 1998). Additionally, sulfate sulfur was run by extraction with KCl on all sampling depths. At the V4 to V6 growth stage (Ritchie et al., 1986), the above ground portion corn was collected from the centers of each treated strip within each grid cell. Additional samples were taken at the R2 growth stage from corn (ear leaves) and soybean (upper most fully developed trifoliate). Plants were dried and weighed to determine plant weight. Fields were harvested with a research grade combine in which the middle 60 feet of each individual treatment within a grid cell was harvested, and a subsample of grain was taken for analysis of sulfur content.

Results and discussion

Analysis of strip mean data at each location showed no significant ($P \leq 0.05$) increase in yield at any location in spite of large variations in numerical values within treatments (Table 2). For example, at Albert Lea the control treatment averaged 168 bu/ac while the N + S treatment was 212 bu/ac. It is likely that the large variation in potential for yield response across some locations were affecting the analysis. Large variations in soil test values may influence the potential for yield responses within individual locations. Soil test phosphorus and sulfur were used to compare treatment responses but results were inconclusive therefore data are not shown. The relationship between 0-6" soil test sulfur and yield response to sulfur was better correlated than any other factor. Data in Figure 1 shows yield response to sulfur compared to soil organic matter level at Clarkfield, Clarks Grove, and Albert Lea. Data from Isanti was left out due to potential interactions with low soil test P within that location. The regression between soil organic matter (0-6") and yield response to sulfur shows a yield increase until 2.6% (r^2=0.39). However, several points from Albert Lea included in the data set appeared to be responsive to a higher soil organic matter value. These data points were excluded from the analysis, but their inclusion only resulted in a change of 0.1%. This data was used to divide soil organic matter levels into Low, Medium, and High levels to analyze individual areas within the trials separately similar to an analysis conducted by Bermudez and Mallarino (2002).

Since relative yields were generally lower when soil organic matter levels were below 2.0% this value was considered Low. Responses above 4.0% were rarely seen therefore this level was considered High. Yield responses were sometimes between 2.0 and 4.0% therefore this level was considered to be Medium. Figure 2 shows the analysis by soil organic matter levels for each location. At Clarkfield organic matter levels were Medium and High and there was no response to any starter or sulfur treatment at his location (LSD $P \leq 0.05$). At Isanti all cells fell in the low category but there was no significant yield response. This was likely due to interactions between low P and S at this location. In addition this site was significantly limited by soil moisture mid to late in the growing season which caused some plots to have very low yields limiting the potential for yield responses. This field would likely see a high potential for response to sulfur during most years. At Clarks Grove the trial was divided into both Low and Medium organic matter values, but yields were only increased by sulfur when organic matter levels were Low (<2.0%). In this case single degree of freedom contrasts indicated a significant increase in yield from sulfur applied as a starter. This field also tested low is soil P, but there was no evidence of a yield increase due to this nutrient. It was surprising that broadcast sulfur did not increase yields compared to starter applied sulfur. This effect could be a result of the band placement or a potential interaction between nitrogen and sulfur which could not be determined with the experimental design. The Albert Lea location had the greatest differences in soil organic matter levels with areas testing Low, Medium, and High. These areas represented hilltop, sideslope, and toeslope positions, respectively. When soil organic matter was High there was no yield increase from sulfur or starter fertilizer treatments and yield potential was the highest within the field. When soil organic matter levels were Low sulfur increased yields the greatest and nitrogen increased yields slightly less. This indicates that sulfur may give the greatest potential yield increase at these organic matter levels, but nitrogen may also influence yield and may be an important factor as well. When soil were greater than 2.0% but less than 4.0% the starter applied sulfur resulted in the greatest yield increase while starter N and broadcast S also increased yields, but not at the same magnitude. It is likely that for similar field the application of sulfur would generally result in a positive yield benefit and that targeted application of sulfur may provide the best return for a corn producer.

Since the Albert Lea location had the largest potential yield increase than the other sites, an analysis was done within that location to study different predictors for yield increases due to sulfur. Both plant and soil factors were considered with the yield response to applied sulfur. Plant response data are given in Figure 3. Four factors were considered, V5 whole plant sulfur concentration, V5 sulfur uptake (concentration times individual plant mass), ear leaf sulfur concentration at R2, and sulfur concentration in the harvested grain. Sulfur concentration at V5 provided the poorest correlation with response to sulfur. In fact there was no significant relationship between the two variables. The correlation was better for both V5 sulfur uptake and ear leaf sulfur concentration but was the greatest between grain sulfur concentration and response to applied sulfur. This indicates that plant analysis is a better predictive tool when samples are collected later in the season. However, this late of a collection date does not allow for any corrective measures if a deficiency is detected. The relationship with sulfur uptake at V5 is somewhat surprising. However, examination of the data shows some a few significantly higher points that are likely affecting the relationship. If those points were deleted it is likely that there would be a poorer relationship between uptake and yield response to sulfur. Visual deficiency symptoms were seen at this location early in the season. However, their appearance may not have been fully reflected in final yield of the plant.

Soil test sulfur collected prior to planting did not correlate well to final yield (Figure 4). The test used in this instance was KCl extractable S which differs from the recommended test for the north central region. However, in other research we have not seen a better correlation with other tests and yield (data not shown). A two foot sample was used in this case but there still was no effect when considering soil test sulfur concentration. However, when sulfur was converted into lbs per acre there was a significant linear relationship. When considering the R^2 value there was little predictability of final yield (R^2=0.16). The best relationship was seen with 0-6" soil organic matter concentration. At this location there appeared to be increases in yield up to about 7.5% soil organic matter concentration within the top 6 inches. This is higher than other research and may be reflective of a higher potential for sulfur response at this particular field in during the year of the study. It does appear that soil test sulfur may be the best predictor before planting of where a response to sulfur may occur.

Conclusions

Sulfur concentration in the grain and soil organic matter concentration in the top 6 inches provided the best predictors of where a sulfur response will occur. Sulfur fertilization increased corn yields consistently when soil organic matter levels were below 2.0% and sometimes between 2.0 and 4.0%. Since the data provided applied sulfur at the same rate, we cannot determine the amount of sulfur that should be applied. Further research is needed to establish whether rates need to be varied for the differing organic matter levels.

References

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Table 1. Soil test averages across grid cells for corn locations from the 0-6, 6-12, and 12-24" soil depths.

Year	Location	County	Soil† Series	Soil† Class	Depth	Soil Test (0-6") Olsen P	Soil Test (0-6") Potassium	Soil Test (0-6") pH	SOM[I] AVG	SOM[I] StDEV	Sulfur[I] AVG	Sulfur[I] StDEV
						-----------ppm-----------			----------%----------		-------ppm-------	
Corn Locations												
2008	Clarkfield	Y. Medicine	Nishna	CL	0-6	34	188	6.4	4.3	0.7	4.7	1.6
					6-12	11	130		3.9	0.7	4.9	0.9
					12-24	8	133		3.3	1.0	2.9	0.8
2008	Clarks Grove	Freeborn	Lester	L	0-6	11	96	6.4	2.0	0.6	9.1	1.1
					6-12	6	84		1.7	0.6	3.2	1.3
					12-24	7	89		1.6	1.0	2.8	0.8
2008	Isanti West	Isanti	Zimmerman	FSL	0-6	9	86	7.8	0.7	0.2	8.7	2.2
					6-12	5	57		0.4	0.2	5.3	2.1
					12-24	6	48		0.2	0.2	5.9	1.6
2009	Albert Lea	Freeborn	Hamel/Lester	L	0-6	22	155	6.4	3.9	2.1	5.3	0.7
					6-12	16	79		3.9	2.6	4.8	1.0
					12-24	9	89		3.1	1.7	4.5	0.7

† Cl, clay loam; L, loam; FSL, fine sandy loam; SL, silt loam

I AVG, average across grid cells; StDEV, standard deviaiton across grid cells.

Table 2. Corn grain yield average values across trial locations for treatment with and without sulfur. Treatments means within locations with the same letter following numbers are not significantly different (LSD P≤0.05)

County	No Starter† - S	No Starter† + S	Starter N - S	Starter N + S	Starter N + P - S	Starter N + P + S	*P*>F
	------------------------------bu./acre------------------------------						
Clarkfield	161	162	164	161	164	165	ns
Clarks Grove	160	159	164	176	160	171	ns
Isanti	85	82	77	83	79	90	ns
Albert Lea	168	187	188	212	193	203	ns

† No Starter, strip average that did not receive starter fertilizer without (-S) and with (+S) broadcast sulfur.

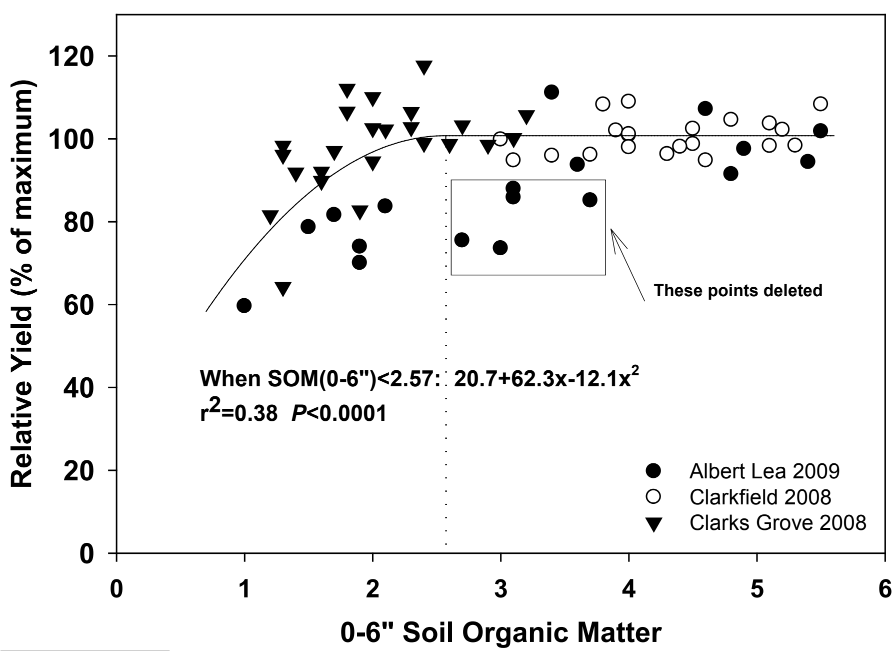

Figure 1. Comparison of relative corn yields for treatments with and without sulfur versus soil organic matter (0-6") at all locations with clay- or loam soil textures. Points within the outlined box were not included in the final data analysis

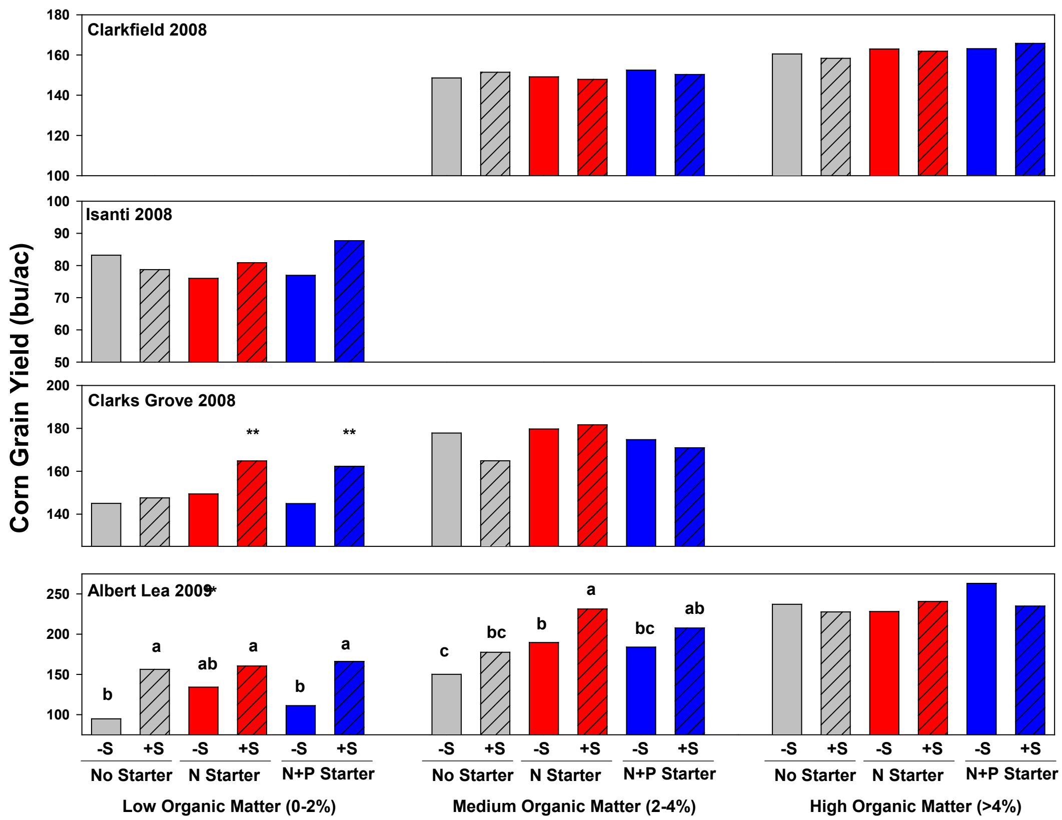

Figure 2. Analysis of actual corn grain yield by soil organic matter level at each location for Low (0-2%), Medium (2-4%), and High (>4%) levels in the top 6" of soil based on data in Figure 1. Small letters above bars represent LSD values (P≤0.05) within organic matter levels. (**. Indicates a significant response according to single degree of freedom contrasts)

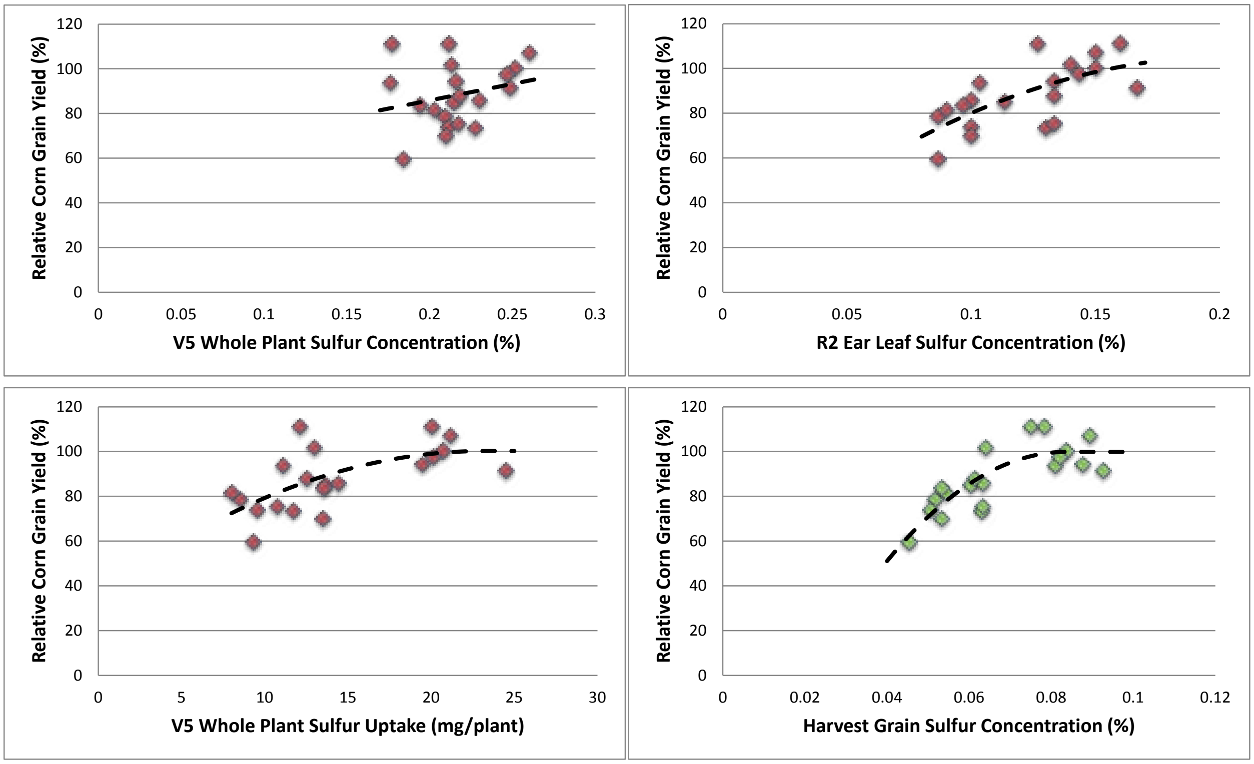

Figure 3. Summary of V5 sulfur concentration, V5 sulfur uptake, ear leaf sulfur concentration at R2, and sulfur concentration in the harvested grain versus yield response to applied sulfur at the Albert Lea location in 2009.

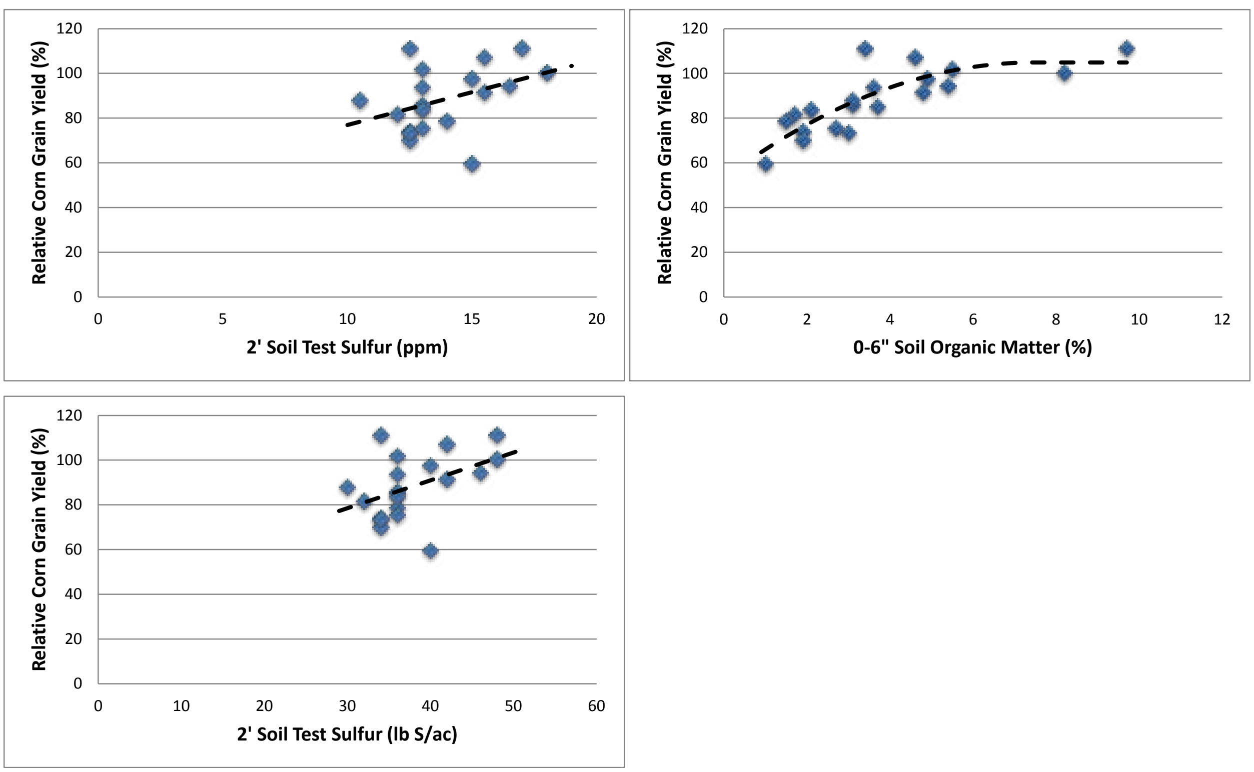

Figure 4. Soil test summaries for samples collected in Spring 2009 prior to treatment application versus yield response to applied sulfur. Yield response was compared to sulfur concentration and total sulfur (lbs/ac) in a 2' composite soil sample and soil organic matter concentration in the top six inches.