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FINAL REPORT

UNIVERSITY OF MINNESOTA - SWROC SULFUR PROJECT

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Tillage and Sulfur Management for Corn in Fine Textured Soils

***Final Summary** – Corn yield data showed a significant interaction between crop rotation, year, sulfur application and tillage system for the corn following corn and soybean following corn rotations. Grain yield response to sulfur mainly occurred under conservation tillage systems which supports the hypothesis that corn grain yield would respond positively to sulfur application under reduced tillage in fine textured soil in southwest Minnesota. Sulfur application before soybean did not affect soybean grain yield. Corn grain moisture from nonsulfur fertilized treatments either equaled or exceeded corn grain moisture from sulfur fertilized treatments. Ear leaf sample nitrogen and sulfur data collected at tassel and converted to N:S ratio was a useful tool for understanding and explaining the relationship between corn grain yield and applied sulfur. Soil test sulfate was a poor indicator of available sulfur.*

INTRODUCTION

Research to date has not established a consistent, predictable yield response to sulfur for non-sandy or medium-high organic matter soils. Sulfur occurs in soils in organic and inorganic forms, with organic sulfur accounting for more than 95% of the total sulfur in most soils. Research conducted in the early 1970's by Iowa researchers showed that many soils in the Midwest were at or near marginal levels of supplying sulfur to crops at that time. Atmospheric deposition of sulfur declined 67%, from 17.7 to 5.9 kg S/ha, between 1979 and 2010 at Lamberton, MN. The reduction has been attributed to a number of factors including: decreased use of sulfur containing fertilizers and pesticides, increased crop yields, reduced emission of sulfur dioxide from petroleum and coal. Soils which originally contained sufficient sulfur may become deficient as agricultural production has intensified and grain yields have steadily increased over the past four decades. The release of plant available sulfur from decomposing crop residue depends on the rate of decomposition and the type and sulfur content of the residue. Addition of crop residues to soils under minimum or no-till systems may reduce plant available sulfur and consequently may lead to increases in sulfur deficiencies and the need for application of sulfur fertilizers.

Current University of Minnesota guidelines indicate that the addition of sulfur should be considered only when corn is grown on coarse textured sandy soils and low organic matter soils. However, some crop producers in southwestern Minnesota have reported that sulfur deficiencies have become more common and more severe in high yield environments. The increased use of more concentrated fertilizers which contain little or no sulfur, combined with less sulfur deposition through precipitation, have decreased the supply of sulfur to crops. In addition, accumulation of crop residues under minimum tillage systems may reduce plant available sulfur and consequently may lead to increases in sulfur deficiencies and the need for application of sulfur fertilizers.

Objectives – A study was designed to evaluate the impact of sulfur and tillage system on corn and soybean yield response and nutrient uptake. The objectives of this research were to: (i) evaluate corn yield response to added sulfur to fine textured soils under five different tillage systems, and (ii) measure nitrogen and sulfur uptake into ear leaf tissue at tassel, grain and corn above ground biomass at physiologic maturity.

METHODS

This experiment was conducted in long-term tillage plots established in 1986 at the Southwest Research and Outreach Center near Lamberton, Redwood County, MN. The site consisted of moderately well drained Normania and well drained Ves loam soils. Crop rotations included corn following corn and corn following soybean. Plots were 50 to 70 ft. wide by 75 ft. long and arranged in a randomized complete block design with four replications. Main plot treatments will include: no-tillage, ridge tillage, fall strip tillage, spring disk + field cultivation, and fall moldboard plow. Whole plots were split (subplots) with half of the plot receiving sulfur fertilizer as ammonium thiosulfate (12-0-0-26) at a rate of 25 lbs S/A, and half receiving 0 lbs S/A. Sulfur was applied with the planter in a 2x2 band. To assure nitrogen sufficiency, 200 lb N/A was applied to all treatments. The nitrogen in the sulfur treatments was accounted for and balanced urea. Corn was planted at 34,000 seeds/A in 30-inch rows. Weed and insect control were according to standard practices for the region.

Soil samples will be collected before fertilizer treatment in year one and after harvest in year three from the 0-6, 6-12, and 6-24 inch depths and analyzed for sulfur content. To test for sulfur sufficiency in the plants, 20 ear leaves were collected at initiation of silking from harvest rows and tested for sulfur content. In addition, grain yield and above ground biomass samples were collected at physiologic maturity. Above ground biomass sampling consisted of obtaining the wet weight of all plants from 10 ft. of a non-harvest row. A sub-sample of six plants was weighed, ground, and dried and analyzed for total dry matter, total nitrogen, and total sulfur. Yield determinations were be made by harvesting four rows using a two-row Almaco research grade combine equipped with a computerized weigh cell and distance sensor. Grain samples were collected from the combine. Grain analysis for protein content, total nitrogen, and total sulfur to evaluate corn N:S ratio to test that the crop had sufficient nitrogen and sulfur to attain optimum yield was not complete at the time of this report.

RESULTS

Precipitation – During the four years of this field experiment, precipitation conditions were below normal three out of four years with the other year being above normal (Tables 1 and 2). These conditions were not ideal but represented recent trends in weather in southwestern Minnesota. All four years exhibited various extremes from severe drought to excess precipitation at different times during the year and growing season.

Overall 2008 precipitation was 18% below normal, 23 in., compared to the 30 yr- normal of 28 in. During the growing season, precipitation was at or below normal between January and September (Table 1). During August and September there was extreme soil moisture deficit. Above normal precipitation in October contributed to soil moisture recharge.

Dry conditions continued during 2009 during which precipitation was again below normal (16%), 24 in., compared to the 30 yr- normal (Table 1). Although conditions were dry again during 2009 between January and August, adequate available soil water early in the growing season, timely precipitation during May through August, and cool air temperatures coupled with overall low wind speeds limited crop heat and drought stress. September precipitation was above normal and excess precipitation in October delayed crop harvest. Normal precipitation in October contributed to soil moisture recharge.

In 2010, precipitation was 36% above normal, 38 in., compared to the 30 yr- normal (Table1). Although conditions were wet during 2010, favorable early season growing conditions resulted in greater than expected crop yields. Despite adequate in field subsurface drainage, the crop likely suffered from excess water conditions during 2010, especially during June and September when precipitation was 71 and 253% above normal, respectively (Table 1). Although September precipitation was excessive it did not delay crop harvest.

For 2011, precipitation was 25% below normal, 21 in., compared to the 30 yr- normal (Table 1) Conditions during the first six months of the year were generally favorable for crop production. However, beginning in July precipitation was below normal and persisted through December. Severe drought conditions during the growing season limited crop production.

Grain Yield – Corn grain yield was affected by the main effect of year, by the three-way interactions of crop rotation by year by tillage system and crop rotation by year by sulfur application, as well as by the four-way interaction of crop rotation by year by tillage system by sulfur application (Table 3). Soybean grain yield was affected by the main effects of year and tillage system and by the two-way interaction of year by tillage system (Table 4). The remainder of this section will focus on discussion of the significant three-way interaction, crop rotation by year by sulfur application, as well as the four-way interaction for corn grain. Since there was no measurable treatment effect of sulfur on soybean yield in this experiment only the two-way significant interaction of year by tillage system will be reported.

A positive corn grain yield response was observed two out of four years (50% of the time) when sulfur was applied at 25 lb S/A for a corn-corn rotation and two out of two years (100% of the time) for corn in a soybean-corn rotation in this experiment (Table 5). The addition of 25 lb. S/A was shown to significantly increase corn grain yield for a corn-corn rotation by 10 and 9 bu/A in 2008 and 2011, respectively. A consistent increase in corn grain yield of 4 bu/A was observed for corn in a corn-soybean rotation for both 2009 and 2011. These data show that the difference in yield and consequently response to applied sulfur on fine textured soil was greater for the corn-corn rotation compared to the soybean-corn rotation in southwest Minnesota. A partial explanation for this observation could be due to greater immobilization of sulfur after incorporation of corn residue in the corn-corn rotation compared to the soybean-corn rotation. Soybean could have also changed the soil microbial activity in the corn-soybean rotation and as a result caused changes in the rates of S mineralization.

Corn yield and the process of mineralization are affected by environmental conditions. The conversion of sulfur from organic compounds present in the soil organic matter and crop residues into plant available forms is a microbially mediated process. Mineralization and immobilization of sulfur is influenced by factors that affect microbial activity, most notably temperature, moisture, and pH (Stevenson and Cole, 1999) and also the presence of the substrate to be mineralized. In addition, nutrient and residue additions combined with different tillage management practices may also affect S mineralization and immobilization rates. Linn and Doran (1984), reported that maximum aerobic microbial activity occurred at a soil water content equivalent to 60% of a soils water-filled pore space.

Corn grain yield data exhibited variability among years for the corn-corn rotation (Table 4). Although soil moisture was not directly measured in the experiment, monthly precipitation was used as a proxy for field conditions. Corn grain yield response to sulfur was significant in 2008 and 2009, while annual precipitation for 2008, 2009 and 2011 was below normal and thus not a good indicator of corn yield response to sulfur application. Examining precipitation at a finer scale, quarterly precipitation during the period July to September, showed that relatively low precipitation amounts in 2008 and 2011 may have had an effect on corn grain yield response to sulfur (Table 2). Analysis of the July-September mean precipitation over this four year period showed that below a threshold of 8.4 inches of precipitation, corn grain yield, expressed as delta yield (the difference in corn grain yield with and without sulfur applied), was affected by sulfur application (Figure 1a). Further analysis showed a similar trend during the month of August; below a threshold of 3.1 inches of precipitation, yield was affected by sulfur application (Figure 1b). Analysis of precipitation for the month of July showed a different pattern. Fitting a quadratic model to the data indicated that below a threshold of 2.9 inches of precipitation, yield was affected by sulfur application (Figure 1c).

Although there was only two years of corn to evaluate from the soybean-corn rotation, precipitation did not appear to be as important of a factor in determining corn grain yield response to sulfur (Table 4). As noted previously, the minimum significant difference in yield between sulfur and no-sulfur treatments was smaller for corn in the soybean-corn rotation (4 bu/A) compared to the corn-corn rotation (9 bu/A).

The results of the four-way interaction among rotation, sulfur treatment, tillage system, and year are shown in Table 6. Averaged across rotation, sulfur treatment, tillage system and year, a positive corn grain yield response to the application of 25 lb S/A was observed 36% of the time in this experiment (Table 6). Most notably, all of the significant responses occurred under conservation tillage systems. In particular, during 2008 and 2011, a positive corn grain yield response to the application of 25 lb S/A was observed 50% of the time for the corn-corn rotation and 40% of the time for the soybean-corn rotation. Additional stored soil moisture and reduce evaporation attributed to the reduced tillage systems, mainly fall strip-till, no-till and spring-disk, are likely contributing factors to increases in corn grain yield. For the corn-corn rotation, fall strip-till, no-till and spring-disk tillage systems resulted in four-year average increases in yield of 12, 9 and 9 bu/A, respectively. For the soybean-corn rotation, the fall strip-till and no-till systems resulted in two-year average increases in yield of 9 and 7 bu/A, respectively. Although there was no significant difference between corn grain yields for the moldboard plow tillage system during the experiment, during 2008 and 2009, the addition of sulfur resulted in non-significant positive corn grain yield responses regardless of rotation. However, for unknown reasons, during 2010 and 2011, the addition of sulfur in the moldboard plow tillage system resulted in non-significant decreased corn grain yield responses irrespective of rotation, although the response approached statistical significance at the 0.10 level in 2011 for the corn-corn rotation.

Soybean grain yield was not affected by the application of sulfur (Table 4). The results of the two-way interaction between tillage system and year are shown in Table 7. Overall, soybean grain yields were greater in 2010, a wet year, compared to 2008, a dry year. During both years the moldboard plow tillage system resulted in the greatest soybean yields while the no-till system resulted in the lowest soybean yields. During 2008, despite abnormally dry conditions, grain yields for the conventionally tilled system out performed the reduced tillage systems (Table 7). This is somewhat unexpected because of the benefits attributed to reduced tillage systems including increased soil water storage and reduced surface soil water evaporation. In contrast, during extremely wet conditions in 2010, as expected, the more aggressive tillage systems outperformed the more reduced tillage systems with the exception of ridge-tillage (Table 7). By design the ridges shed excess water and maintain a more will aerated root zone near the soil surface.

Grain Moisture – Corn grain moisture was affected by the main effect of year, by the three-way interactions of crop rotation by year by tillage system and crop rotation by year by sulfur application, as well as by the four-way interaction of crop rotation by year by tillage system by sulfur application (Table 3). Soybean grain moisture was affected by the main effects of year and tillage system and by the two-way interaction of year by sulfur application and year by tillage system (Table 4). The remainder of this section will focus on discussion of the significant four-way interaction, crop rotation by year by sulfur application for corn grain.

The results of the four-way interaction for corn grain moisture for rotation by sulfur treatment, tillage system and year are shown in Table 8. The main concern of producers is that added sulfur will retard grain drying and delay harvest. Overall, the greatest grain moisture contents were observed in 2008 and the lowest in 2011. Averaged across rotation, sulfur treatment, tillage system and year, a significant corn grain moisture response to the application of 25 lb S/A was observed 13% of the time in this experiment (Table 8). Generally, when sulfur was applied percent grain moisture was equal to or lower than when no sulfur was applied.

Ear Leaf N:S – Nitrogen and sulfur are both required for protein formation. Several studies have shown that yield response to sulfur is greater with increasing rates of nitrogen fertilizer (Reisnauer and Dickinson, 1961; Rabuffetti and Kamprath, 1977). Plant sulfur status is often expressed as the ratio of total nitrogen to total sulfur (N:S ratio). It has been suggested that the N:S ratio may be a better indicator of the sulfur status of corn than sulfur concentration (Stewart and Whitefield, 1969; Reneau, 1983). Stewart and Porter (1969) reported that when sulfur is deficient, the ratio of total nitrogen to total sulfur will generally exceed 15:1.

Ear leaf N:S ratio was affected by the main effect of year and by the three-way interactions of crop rotation by year by tillage system, crop rotation by year by sulfur application and the four-way interaction of crop rotation by year by tillage system by sulfur application (Table 3). The remainder of this section will focus on discussion of the significant four-way interaction, crop rotation by year by tillage system by sulfur application for corn grain N:S ratio.

The results of the four-way interaction for ear leaf N:S ratio for rotation by year by tillage system by sulfur treatment shown in Table 9. A positive response is indicated by a decrease in ear leaf N:S ratio when 25 lb S/A fertilizer sulfur was applied. A positive ear leaf N:S ratio response was observed all four years (100% of the time) when sulfur was applied at 25 lb S/A for a corn-corn rotation and two out of two years (100% of the time) for corn in a soybean-corn rotation in this experiment (Table 9). During 2009, with the exception of moldboard plow for the soybean-corn rotation, the nonsulfur fertilized treatments resulted in ear leaf N:S ratios greater than the 15:1 threshold indicating an insufficient supply of sulfur to achieve optimum yield (Table 9). However, the data also showed that the sulfur fertilized treatments also had N:S ratios greater than 15:1 (Table 9). The 2009 ear leaf data suggest that sulfur was limiting in both nonsulfur and sulfur fertilized treatments at the time of sampling. Corresponding grain yield data for 2009 indicated that, for both rotations, only the no-till system responded to applied sulfur (Table 6). Sumner (1978) provides a clear, concise discussion for the proper interpretation of nutrient ratios in plant tissue. According to the author, two possible explanations exist when an N:S ratio is above the optimal range. First, nitrogen (content/concentration/availability) is optimal and sulfur (content/concentration/availability) is insufficient; second, nitrogen (content/concentration/availability) is excessive and sulfur (content/concentration/availability) is optimal. The N:S ratio does not distinguish between these two possible scenarios which may exist in the plant. Consequently, when both N:S ratios are above the optimal 15:1 threshold, a response to applied sulfur will only occur if sulfur is limiting; if the condition of excess nitrogen exists and sulfur is optimal, a yield response to sulfur may not necessarily be obtained since other factors may be limiting yield. During 2010, ear leaf N:S ratio data indicated statistically significant differences between nonsulfur and sulfur fertilized treatments (Table 9). However, only ear leaf N:S ratios for fall-strip till, ridge-till, and spring disk till were at or above the 15:1 threshold. Corresponding grain yield data indicated that only the fall-strip till system responded to applied sulfur (Table 6). Three possibilities exist to explain the lack of yield response to applied sulfur for the ridge-till and spring-disk till systems (Sumner, 1978). First, nitrogen and sulfur (content/concentration/availability) are both optimal; second, nitrogen and sulfur (content/concentration/availability) are both limiting; and third, nitrogen and sulfur (content/concentration/availability) are both excessive. Ear leaf N:S ratio may be helpful in understanding the 13 bu/A decrease in corn grain yield for the sulfur fertilized treatment compared to nonsulfur fertilized treatment for the moldboard plow tillage system in 2010. Two possibilities exist to explain the yield response for the moldboard plow system (Sumner, 1978). First, nitrogen (content/concentration/availability) is optimal and sulfur (content/concentration/availability) is excessive; second, nitrogen (content/concentration/availability) is limiting and sulfur (content/concentration/availability) is optimal. It is possible that under the weather conditions present in 2010, that nitrogen was limiting where sulfur fertilizer was applied for the moldboard plow treatment and consequently limited corn grain yield (Table 6). The ear leaf N:S ratio for the moldboard plow treatment in 2010 was the lowest where sulfur was applied, which also suggests N to be deficient rather than optimal (Table 9). A similar trend and explanation for the moldboard plow data is plausible for 2011. In 2011, ear leaf N:S ratio data indicated statistically significant differences between nonsulfur and sulfur fertilized treatments regardless of rotation (Table 9). However, only ear leaf N:S ratios for fall-strip till, no-till, and ridge-till were at or above the 15:1 threshold. Corresponding grain yield data indicated that fall-strip till and no-till responded to applied sulfur for the corn-corn rotation, and fall-strip till and ridge-till responded to applied sulfur for the soybean-corn rotation (Table 6). Ear leaf N:S ratios for ridge-till under the corn-corn rotation and no-till for the soybean-corn rotation indicated positive responses to applied sulfur but corresponding grain yields did not support these findings. In contrast, the ear leaf N:S ratio for spring-disk under the corn-corn rotation indicated no response to applied sulfur but corresponding grain yield data indicated an 8 bu/A yield increase. In this case nitrogen could have been either excessive or limiting.

Grain N:S – Corn grain N:S ratio was affected by the main effect of year and by the three-way interactions of crop rotation by year by tillage system and crop rotation by year by sulfur application (Table 3). Soybean grain N:S ratio was only affected by the main effect of sulfur application (Table 4). The remainder of this section will focus on discussion of the significant three-way interaction, crop rotation by year by sulfur application for corn grain N:S ratio and the significant effect of sulfur application on soybean grain N:S ratio.

The results of the three-way interaction for corn grain N:S ratio for rotation by sulfur treatment and year are shown in Table 10. A positive corn grain N:S ratio response was observed all four years (100% of the time) when sulfur was applied at 25 lb S/A for a corn-corn rotation and two out of two years (100% of the time) for corn in a soybean-corn rotation in this experiment (Table 10). As with the ear leaf N:S ratio, a positive response is indicated by a decrease in grain N:S ratio when 25 lb S/A fertilizer sulfur was applied. This indicates that there is relatively more sulfur in the grain when sulfur is applied compare to the nonsulfur fertilized treatment. Over the four year experiment, at harvest, nonsulfur fertilized corn grain always had N:S ratios greater than sulfur fertilized treatments regardless of rotation (Table 10). During 2008 and 2009, in the nonsulfur fertilized corn-corn rotation, the grain N:S ratio was greater than 15:1 indicating an insufficient supply of sulfur to achieve optimum yield (Table 10). In 2010 and 2011, the corn grain N:S ratios indicated borderline sulfur deficiency for the corn-corn rotation (Table 10). As reported previously, corn grain yield data indicated no significant main effect of sulfur in 2009 or 2010, but showed a significant response to sulfur addition in 2008 and 2011 (Table 5). Corn grain yield in 2009 and 2010 was greater than in 2008 and 2011, which would suggest greater requirement of nutrient supply from the soil. As reported previously, sulfur supply in the soil is a process mediated by soil microbes, and it is possible that in 2009 and 2010, those same microbes also had a higher demand for the same nutrients as the corn plants. A competition for the same nutrients between plants and microbes would likely decrease nutrient availability for plant uptake. Rainfall data from July to September also shows higher precipitation in 2009 and 2010 compared with 2008 and 2011, and microbes are known to be more active in the presence of adequate moisture. Though contradictory, these results show that we do not fully understand the interactions between soil nutrients and how the soil microbiology affects their availabilities.

During 2009 and 2011, both the sulfur and nonsulfur fertilized corn in the soybean-corn rotation had grain N:S ratios less than 15:1, indicating a sufficient supply of sulfur to achieve optimum yield (Table 10). Although the grain N:S ratio for corn in the soybean-corn rotation indicated sufficient sulfur for optimal yield, grain yield data indicated a sulfur response in both years (Table 5). When corn grain material from mature plants is used for analysis, as the data from this experiment suggests, the ratio of nitrogen to sulfur of 15:1 may not be accurate and in fact may be too large. Overall, the difference between nonsulfur fertilized and sulfur fertilized treatments was greater for the corn-corn rotation compared to the soybean-corn rotation (Table 10). On average, the difference between N:S ratio for nonsulfur fertilized and sulfur fertilized treatments for the corn-corn rotation was 2 (range 1.6-2.3). In contrast, the mean difference between N:S ratio for nonsulfur fertilized and sulfur fertilized treatments for the soybean-corn rotation was 1.2. These differences between rotations could be attributed to the quantity and quality of plant residue and the mineralization and immobilization of sulfur from soil organic matter.

For oil crops such as soybean, sulfur is particularly important because oil crops require more sulfur than cereal grains. The main effect of sulfur application on soybean grain N:S ratio resulted in a N:S ratio of 21 for nonsulfur fertilized soybean and 19 when 25 lb S/A was applied before soybean. Dijkshoorn and van Wilk reported that leaf N:S ratio for leguminous plants to be 17:1 (1967). Although the N:S ratio results for soybean in this experiment suggest sulfur to be limiting for soybean there was no effect of sulfur on soybean yield detected (Table 4). It is also possible that other nutrient/nutrients was limiting soybean yield which could have led to a higher uptake of N, and therefore, the higher N:S ratio observed without a response to sulfur application.

Corn Biomass – Above ground corn biomass was affected by the main effect of year, by the three-way interactions of crop rotation by year by tillage system and crop rotation by year by sulfur application (Table 3). The remainder of this section will focus on discussion of the significant three-way interaction, crop rotation by year by sulfur application for above ground corn biomass.

The results of the three-way interaction for above ground corn biomass for rotation by year by sulfur application are shown in Table 11. The lowest above ground corn biomass for the corn-corn rotation was observed during 2008. This was most likely due to overall below average precipitation between January and September resulting in poor growing conditions in 2008 (Table 1). The greatest above ground corn biomass for the corn-corn rotation was observed during 2009. In 2009, the nonsulfur fertilized corn-corn rotation resulted in above ground biomass 0.9 ton less than the sulfur fertilized corn (Table 11). However, there was no difference in sulfur and nonsulfur fertilized corn grain yield for the corn-corn rotation in 2009 (Table 5). In 2011, the nonsulfur fertilized soybean-corn rotation resulted in above ground biomass 0.6 ton less than the sulfur fertilized corn (Table 11). Corn grain yield data from 2011 showed a corresponding yield increase when sulfur was applied (Table 5). In contrast, although the application of sulfur resulted in a corn grain yield increase for the soybean-corn rotation in 2009, there was no difference in sulfur and nonsulfur fertilized above ground corn biomass in 2009 (Table 11).

Biomass N:S – Above ground biomass N:S ratio was affected by the main effect of year and by the three-way interactions of crop rotation by year by tillage system and crop rotation by year by sulfur application (Table 3). The remainder of this section will focus on discussion of the significant three-way interaction, crop rotation by year by sulfur application for above ground biomass N:S ratio.

The results of the three-way interaction for above ground biomass N:S ratio for rotation by sulfur treatment and year are shown in Table 12. A positive above ground biomass N:S ratio response was observed all four years (100% of the time) when sulfur was applied at 25 lb S/A for a corn-corn rotation and two out of two years (100% of the time) for corn in a soybean-corn rotation in this experiment (Table 12). Over the four year experiment, at harvest, nonsulfur fertilized above ground biomass always had N:S ratios greater than sulfur fertilized treatments regardless of rotation. During 2009 and 2011, in the nonsulfur fertilized corn-corn rotation, the biomass N:S ratio was greater than 15:1 indicating an insufficient supply of sulfur to achieve optimum yield (Table 12). Surprisingly, corresponding corn grain yield data for 2009, for the corn-corn rotation, indicated no significant main effect of applied sulfur in 2009 (Table 5). However, grain yield data showed an interaction effect of sulfur by tillage for no-till in 2009 (Table 6). During 2011, the above ground biomass N:S ratio indicated sulfur deficiency for the corn-corn rotation. Correspondingly, grain yield data indicated a significant positive main effect of sulfur on corn grain yield in 2011 (Table 5). In addition, grain yield data showed an interaction effect of sulfur by tillage for fall-strip till, no-till and spring disk in 2011 (Table 6). Above ground biomass N:S ratios for nonsulfur and sulfur fertilized treatments were below 15:1 in 2008 and 2010 for the corn-corn rotation, indicating adequate sulfur for optimum yield (Table 12). Although the 2008 above ground biomass N:S ratio results indicated that no sulfur was required, corresponding grain yield data for the corn-corn rotation showed a 10 bu/A positive yield response to applied sulfur (Table 5). These conflicting data raise questions whether the N:S ratio of 15:1 threshold for corn is accurate. It is possible that the N:S threshold ratio for sulfur could in fact be lower than 15:1 or that the interaction of tillage has an impact on the N:S ratio. In addition, it might also be possible that different parts of the corn plant have different N:S threshold values, which would therefore, change during the life cycle of the plant. Further investigation is warranted to determine whether tillage system has an impact on N:S threshold ratio.

Soil Sulfate – The results from the soil sulfate test were contradictory and had little relationship with the results observed. Baseline soil samples were collected in 2008 before the initial application of sulfur from the depths o 0 to 6", 6 to 12" and 12 to 24". Soil samples were collected again in 2011 at the end of the study from all plots, including all rotations, tillage, and sulfur treatments for the same depths described above. Analysis of variance showed that neither the main effects of tillage, rotation, and depth no their interactions were significant effects; however, there was a significant interaction effect between time and depth (Table 13). At the 0 to 6" depth, the results showed a consistent decrease in soil test sulfur from 2008 to 2011 regardless of sulfur addition (Table 14). At the 6 to 12" depth, there were no significant changes in soil test sulfur (Table 14). And at the 12 to 24" depth, there was an increase in both plots that received the nonsulfur and the sulfur treatments (Table 14). Soil test sulfur from 2008 was compared with grain yield, biomass yield, sulfur content and uptake, and N:S ratios observed in 2008, and soil test sulfur from 2011 was compared with grain yield, biomass yield, sulfur content and uptake, and N:S ratios observed in 2011. However, this comparison showed no relationship between soil test sulfur levels and the measured parameters, indicating that the soil test sulfur is a poor predictor of available sulfur in soils. Based on the results observed for soil test sulfur and the above ground plant parameter measured, this research suggests that other tools for predicting available sulfur in soil form southwest Minnesota for corn production needs to be developed.

CONCLUSIONS

The objectives of this research were to: (i) evaluate corn yield response to added sulfur to fine textured soils under five different tillage systems, and (ii) measure nitrogen and sulfur uptake into ear leaf tissue, grain and corn above ground biomass. Corn grain yield data exhibited variability among years mainly due to the effect of changing weather patterns and the frequency and amount of precipitation. Total precipitation for July plus total July through September precipitation were good predictors of corn response to applied sulfur. The data also showed that the difference in yield and consequently response to applied sulfur on fine textured soil was greater for the corn-corn rotation compared to the soybean-corn rotation in southwest Minnesota. The addition of 25 lb. S/A was shown to significantly increase corn grain yield for a corn-corn rotation by about 10 bu/A. A consistent increase in corn grain yield of 4 bu/A was observed for corn in a corn-soybean rotation. A partial explanation for this observation could be due to greater immobilization of sulfur after incorporation of corn residue in the corn-corn rotation compared to the soybean-corn rotation. Generally, when sulfur was applied percent grain moisture was equal to or lower than when no sulfur was applied. Ear leaf N:S ratios, an expression of the relative proportion of total nitrogen and total sulfur in plant tissue, was useful in explaining grain yield results. However, as a diagnostic tool for addressing potential in season plant needs, ear leaf analysis would not useful. The results from soil sulfate testing were contradictory and had little relationship with the results observed. Based on the results observed for soil test sulfur and the above ground plant parameter measured, this research suggests that other tools for predicting available sulfur in soil form southwest Minnesota for corn production needs to be developed.

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Table 1. Monthly precipitation, and departure from 30-year normal for the period 2008-2011, near Lamberton, MN

Month	Year								
	2008		2009		2010		2011		30-year Normal
	precip. (in)	depart. (%)	precip. (in)	depart. (%)	precip. (in)	depart. (%)	precip. (in)	depart. (%)	precip. (in)
January	0.1	-83	0.3	-50	0.9	50	1.0	67	0.6
February	0.1	-83	0.6	0	0.7	17	1.6	167	0.6
March	1.3	-24	1.1	-35	1.3	-24	1.5	-12	1.7
April	3.0	0	1.5	-50	2.5	-17	2.6	-13	3.0
May	3.2	-6	1.6	-53	2.0	-41	4.2	24	3.4
June	3.6	-12	3.2	-22	7.0	71	5.1	24	4.1
July	3.3	-15	2.0	-49	3.8	-3	3.7	-5	3.9
August	0.6	-85	3.1	-23	4.8	20	0.4	-90	4.0
September	2.1	-30	3.3	10	10.6	253	0.2	-93	3.0
October	4.2	110	4.9	145	2.0	0	0.4	-80	2.0
November	1.0	-29	0.4	-71	1.0	-29	0.0	-100	1.4
December	0.8	33	1.9	217	1.4	133	0.5	-17	0.6
Total	**23.3**	-	**23.9**	-	**38.0**	-	**21.2**	-	**28.3**

Table 2. Quarterly precipitation for the period 2008-2011, near Lamberton, MN

Period	2008	2009	2010	2011	30-year Normal
Jan. – Mar.	1.5	2.0	2.9	4.1	2.9
Apr. – June	9.8	6.3	11.5	11.9	10.5
July – Sept.	6	8.4	19.2	4.3	10.9
Oct. – Dec.	6	7.2	4.4	0.9	4

Table 3. Analysis of variance table for corn: grain yield and moisture, Leaf N:S,biomass yield, biomass N:S ratio and grain N:S ratio.

Source of variation	Yield	Grain moisture	Grain N:S	Leaf N:S	Aboveground biomass	Biomass N:S
			--------- Pr. > F ---------			
Year (Y)	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**0.0005**
R (Y x T)	**<0.0001**	**<0.0001**	**0.0597**	**0.0085**	**0.0002**	**0.0721**
R (Y x S)	**0.0042**	**0.0002**	**<0.0001**	**<0.0001**	**0.0735**	**<0.0001**
R (Y x T x S)	**0.0114**	**0.0563**	0.2739	**0.0062**	0.2840	0.2965

Rotation (R), Tillage (T), Sulfur (S). Probability level for significant treatment effect is 0.10.

Table 4. Analysis of variance table for soybean: grain yield and moisture, and grain N:S ratio.

Source of variation	Yield	Grain moisture	Grain N:S
Year (Y)	**<0.0001**	**<0.0001**	0.3642
Sulfur (S)	0.4231	0.5834	**<0.0001**
Tillage (T)	**<0.0001**	**0.0001**	0.1700
Y x S	0.6287	**0.0230**	0.4108
Y x T	**0.0003**	**<0.0001**	0.5817
T x S	0.2861	0.7971	0.7139
Y x T x S	0.8466	0.6539	0.8717

Probability level for significant treatment effect is 0.10.

Table 5. Summary of corn grain yield for rotation by sulfur treatment and year.

Sulfur (lb/A)	Corn grain yield (bu/A)			
	corn-corn			
	2008 (LSD=6)	2009 (LSD=4)	2010 (LSD=4)	2011 (LSD=4)
0	100	179	177	153
25	110	182	178	162
	soybean-corn			
0	-	188	-	170
25	-	192	-	174

P-level = 0.10.

Table 6. Summary of corn grain yield for rotation by sulfur treatment, tillage system and year.

		Corn grain (bu/A)				
Rotation	Sulfur (lb/A)	Fall-strip	Moldboard	No-till	Ridge-till	Spring-disk
		2008 (LSD = 11)				
corn-corn	0	93	107	84	113	102
corn-corn	25	105	113	102	114	117
		2009 (LSD = 8)				
corn-corn	0	175	195	168	184	171
corn-corn	25	176	199	177	180	178
soybean-corn	0	184	207	177	181	194
soybean-corn	25	190	211	185	180	193
		2010 (LSD = 8)				
corn-corn	0	172	194	161	180	178
corn-corn	25	182	181	160	184	184
		2011 (LSD = 8)				
corn-corn	0	140	162	148	162	156
corn-corn	25	166	155	157	169	164
soybean-corn	0	163	182	163	164	179
soybean-corn	25	174	176	168	173	179

P-level = 0.10.

Table 7. Summary of soybean grain yield for tillage system by year.

	Soybean grain yield (bu/A)				
Year	Fall-strip	Moldboard	No-till	Ridge-till	Spring-disk
2008	41c	46a	39c	40c	43b
2010	51c	59a	45d	55b	54b

Values within a row followed by a different lowercase letter are significant at P-level = 0.10.

Table 8. Summary of corn grain moisture for rotation by tillage system, sulfur treatment and year.

		Corn grain moisture (%)				
Rotation	Sulfur (lb/A)	Fall-strip	Moldboard	No-till	Ridge-till	Spring-disk
			2008 (LSD = 0.8)			
corn-corn	0	18.5	17.6	20.6	17.4	17.4
corn-corn	25	17.8	17.6	19.1	16.7	17.3
			2009 (LSD = 0.6)			
corn-corn	0	19.0	17.4	18.5	18.3	17.7
corn-corn	25	18.6	17.4	18.1	18.2	17.1
soybean-corn	0	18.6	17.2	18.6	18.2	17.3
soybean-corn	25	18.2	17.1	18.3	18.0	17.0
			2010 (LSD = 0.6)			
corn-corn	0	18.6	15.4	18.1	16.0	16.9
corn-corn	25	17.9	15.2	17.8	16.3	15.9
			2011 (LSD = 0.6)			
corn-corn	0	12.6	12.5	12.3	12.5	12.5
corn-corn	25	12.1	12.3	12.1	12.2	12.3
soybean-corn	0	12.8	12.5	12.3	12.5	12.5
soybean-corn	25	12.3	12.5	12.1	12.2	12.3

P-level = 0.10.

Table 9. Summary of corn ear leaf N:S ratio for rotation by sulfur treatment, tillage system and year.

		Corn ear leaf N:S ratio				
Rotation	Sulfur (lb/A)	Fall-strip	Moldboard	No-till	Ridge-till	Spring-disk
				2009 (LSD = 0.6)		
corn-corn	0	16.2	16.4	16.5	16.6	17.0
corn-corn	25	15.3	15.7	15.7	15.4	15.0
soybean-corn	0	16.3	15.8	16.3	16.1	16.1
soybean-corn	25	15.8	15.4	15.3	15.6	15.2
				2010 (LSD = 0.7)		
corn-corn	0	15.1	14.3	14.4	15.0	15.3
corn-corn	25	13.4	12.9	13.4	12.6	13.5
				2011 (LSD = 0.6)		
corn-corn	0	15.8	13.8	15.5	15.3	14.8
corn-corn	25	13.4	13.0	13.5	13.1	12.6
soybean-corn	0	15.2	14.1	15.2	15.6	14.6
soybean-corn	25	14.0	13.3	13.8	13.3	13.6

P-level = 0.10.

Table 10. Summary of corn grain N:S ratio for rotation by sulfur treatment and year.

Sulfur (lb/A)	Corn grain N:S ratio			
	corn-corn			
	2008 (LSD=0.7)	2009 (LSD=0.5)	2010 (LSD=0.5)	2011 (LSD=0.5)
0	18.0	15.7	15.0	14.9
25	15.7	13.9	13.4	12.6
	soybean-corn			
0	-	14.8	-	14.1
25	-	13.6	-	12.9

P-level = 0.10.

Table 11. Summary of corn biomass for rotation by sulfur treatment and year.

Sulfur (lb/A)	Corn biomass (ton/A)			
	corn-corn			
	2008 (LSD=0.8)	2009 (LSD=0.6)	2010 (LSD=0.6)	2011 (LSD=0.6)
0	3.6	7.2	7.4	6.7
25	3.4	8.1	6.9	6.2
	soybean-corn			
0	-	8.6	-	7.4
25	-	8.8	-	6.8

P-level = 0.10.

Table 12. Summary of corn biomass N:S ratio for rotation by sulfur treatment and year.

Sulfur (lb/A)	Corn biomass N:S ratio			
	corn-corn			
	2008 (LSD=1.8)	2009 (LSD=1.4)	2010 (LSD=1.5)	2011 (LSD=1.4)
0	13.1	15.9	14.2	22.2
25	11.1	14.0	12.2	15.7
	soybean-corn			
0	-	14.9	-	19.5
25	-	12.9	-	14.8

P-level = 0.10.

Table 13. Analysis of variance table for soil test sulfur N:S ratio.

Source of variation	0-6"	0-12"	12-54"
Tillage (T)	0.409	0.759	0.742
Rotation (R)	0.713	0.804	0.576
Time (Time)	**0.001**	0.100	**0.001**
T x R	0.584	0.712	0.451
T x Time	0.605	0.341	0.175
R x Time	0.540	0.546	0.754
T x R x Time	0.595	0.902	0.465

Probability level for significant treatment effect is 0.10.

Table 14. Summary of pre- and post-experiment soil testing for sulfate.

Sampling Depth (inches)	Soil Sulfate Levels (ppm)		
	2008	2011	
		0	25
0-6" (LSD = 0.73)	5.73	3.36	3.58
6-12" (LSD = 0.83)	3.65	3.01	3.66
12-24" (LSD = 0.83)	1.87	2.95	3.84

P-level = 0.10.

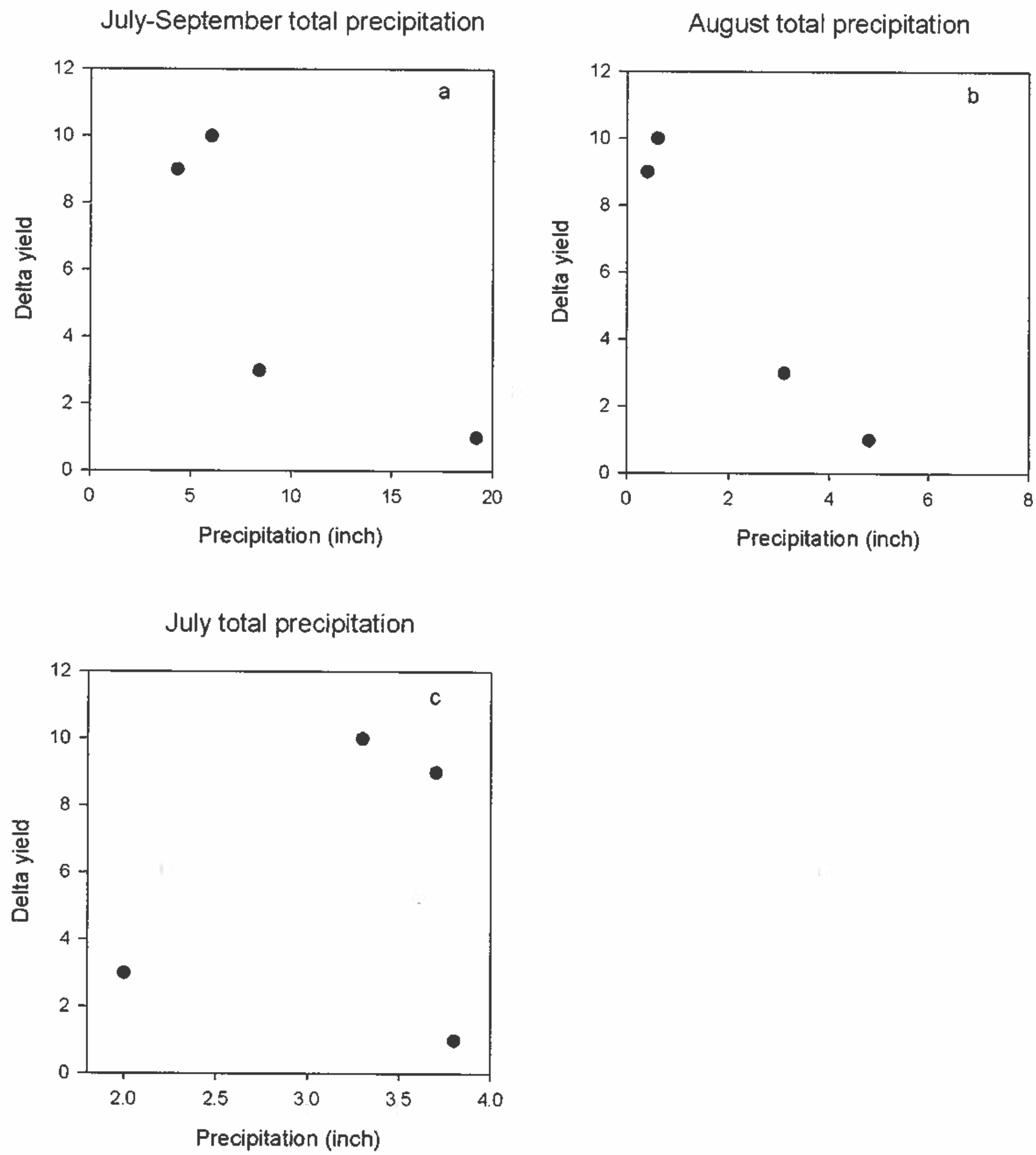

Figure 1. Monthly precipitation, by year, versus delta yield near Lamberton, MN for the period 2008-2010.