WITHIN-FIELD SPATIAL VARIABILITY IN OPTIMAL SULFUR RATES FOR CORN IN MINNESOTA: IMPLICATIONS FOR PRECISION SULFUR MANAGEMENT

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Abstract. *The ongoing decline in sulfur (S) atmospheric depositions and high-yield crop production have resulted in S deficiency and the need for S fertilizer applications in corn cropping systems. Many farmers are applying S fertilizers uniformly across their fields. Little has been reported on the within-field spatial variability in optimal S rates and the potential benefits of variable rate S applications. The objectives of this study were to 1) assess within-field variability of optimal S rates (OSR) and 2) evaluate the potential benefits of variable rate S application in corn fields. Three on-farm S trials were conducted in western and southeastern Minnesota in 2022. In a randomized complete block design, the trials used five S rates (0, 10, 20, 30, and 40 lb S $^{-1}$ac or 0, 11.2, 22.4, 33.6, and 44.8 kg^{-1}ha). Each field was delineated into grids with a dimension of 70-80 ft (21.34-24.38 m) wide and 150-600 ft (45.72/82.88 m) long, depending on the farmer's applicators. The preliminary results indicated that higher S application rates would benefit two corn fields in western Minnesota where no S fertilizers were conventionally applied. The field in southeastern Minnesota received S applications at 30 lb S ac^{-1} (33.6 kg S ha^{-1}) for the past several years and would benefit from a lower S rate. The OSR varied within all three fields, ranging from 0 to 40 lb ac^{-1}. The farmer's standard application rate of 30 lb ac^{-1} (33.6 kg S ha^{-1}) would be suitable in 15%, 16%, and 37% of the three fields, respectively. These fields did not need any S fertilizers in 11%, 26%, and 25% of the areas. A higher rate of 40 lb ac^{-1} (44.8 kg ha^{-1}) was optimum in 6%, 32%, and 12% of the fields, respectively. The moderate rate of 10-20 lb ac^{-1} (11.2-22.4 kg ha^{-1}) would be optimum in 68%, 25%, and 25% of the fields, respectively. More analyses will be performed to determine the potential economic benefits of site-specific S applications, and the implications for precision S management will be discussed.*

Keywords. *On-farm trial; Variable rate sulfur; Precision sulfur management; Optimal sulfur*

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rate; Sulfur use efficiency.

Introduction

Since 1860, agricultural research has emphasized the importance of sulfur (S) as a vital element essential for plant growth within the farming community (Always, 1940; Bogdanov, 1899; Hart & Peterson, 1911). Sulfur influences the plant's general photosynthetic and metabolic mechanisms and is crucial in synthesizing proteins, chlorophyll, enzymes, and vitamins (Sharma et al. 2024). Sulfur is a vital growth-limiting plant nutrient that plays a pivotal role in facilitating the uptake of essential nutrients such as nitrogen, phosphorus, potassium, molybdenum, zinc, iron, selenium, and boron. This underscores its importance in meeting demand and optimizing broader plant nutrition management.(Abrol & Ahmad, 2003; De Bona & Monteiro, 2010; Amin & El-Eyuoon, 2018).

Historically, atmospheric deposition supplied substantial amounts of sulfur in readily available forms for plant absorption, naturally meeting crop sulfur demands without the need for additional fertilization, as reported by Dick et al. (2008). However, due to contemporary environmental policies to enhance air quality and sustainability, atmospheric sulfur deposition has dramatically decreased by 80% over the past 30 years (EPA 2024; Hinckley and Driscoll, 2022; Ralph E. Baumgardner et al. 2002; Vieira-Filho et al. 2015). Along with this decline, other factors have increased sulfur deficiency in agricultural systems. Intensive agricultural practices and the usage of high-yielding crops resulted in an increased crop removal of sulfur from the soil. Reduced tillage intensity (Sutradhar et al. 2017), increased use of low-sulfur-content fertilizers, and decreased use of sulfur-containing fungicides and insecticides (Eriksen et al. 2004; Scherer, 2001) also contribute significantly to this scenario. Since organic matter corresponds to approximately 95% of total soil sulfur , the loss of soil organic matter has also reduced the available sulfur (Sainz Rozas et al. 2011). Accordingly, these combined factors underscore the necessity of targeted sulfur fertilization strategies to address actual and future crop sulfur requirements.

In the current agricultural landscape, sulfur fertilization has become a critical practice to compensate for the reduced atmospheric deposition and other contributing factors to sulfur deficiency, especially in the U.S. Midwest, a region among the top crop producers worldwide (Hinckley & Driscoll, 2022). Modern sulfur fertilizers, such as ammonium sulfate and gypsum, are commonly used to replenish soil sulfur levels and support optimal crop growth (G. W. Rehm et al. 2008; Kovar 2021; Sharma et al. 2024). These fertilizers are applied at various stages of the crop growth cycle to ensure adequate sulfur availability during critical periods of corn development. This shows that sulfur fertilization can significantly enhance corn yield and quality. However, sulfur management is a recent issue, and widespread under-application and over-application problems lead to inefficiencies that impact crop productivity, environmental sustainability, and farming community profitability (Likens et al. 1996; Kovar 2021; Oenema and Postma 2003).

Precision agriculture and variable-rate fertilization offer a promising solution by optimizing sulfur application rates based on site-specific conditions, thus improving efficiency and reducing environmental impact (Abit et al. 2018; Erickson and Fausti 2021; Hedley 2015). However, more research is needed, particularly in the realm of precision sulfur management. Therefore, this work aims to assess the within-field variability of optimal sulfur rates in on-farm trials in Minnesota and evaluate their agronomic, economic, and environmental benefits. This is essential for understanding, developing, and implementing efficient sulfur management strategies through on-farm experimentation.

Material and Methods

Study Sites and Experimental Design

This study was conducted at three on-farm trial sites in western and southeastern Minnesota during the 2022 growing season (Figure 1). The sites were selected based on the farmer's historical sulfur application practices, varying soil types, and corn as the current crop. Each site was divided into a trial area, where the study design was implemented, and a non-trial area, where the farmer's common fertilizer strategy was used.

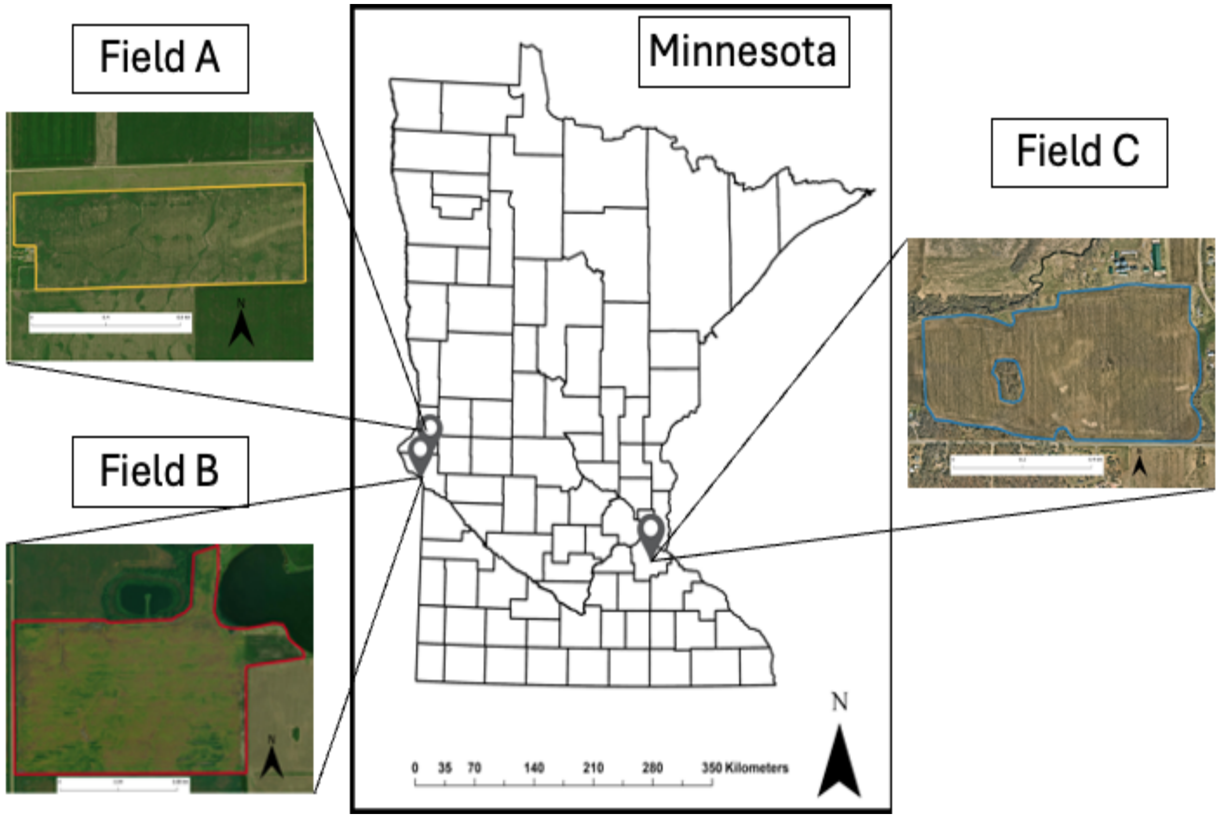

Figure 1. Locations of the on-farm trials conducted in Minnesota during the 2022 growing season, with detailed views of each trial field (Field A, Field B, and Field C). The trials were conducted in western Minnesota and southeastern Minnesota.

Field A was located in Western Minnesota, encompassing a trial area of 77 acres. The cultivar used for this field was Ren312, a variety of corn planted on May 25, 2022. Preplant sulfur was applied a day earlier, on May 24, 2022, in the form of ammonium sulfate (AMS). The field was harvested between October 6 and October 9, 2022. The farmer's sulfur rate (FSR) for this field was 0 lb S/ac.

Field B was also situated in Western Minnesota, covering a trial area of 44 acres. The corn cultivar used was DKC45-95RIB, planted on May 18, 2022. Preplant sulfur was applied on May 16, 2022, using ammonium sulfate (AMS). Harvest took place on October 13, 2022. The farmer's sulfur rate (FSR) for this field was set at 0 lb S/ac.

Field C is located in Southeastern Minnesota and spans a trial area of 55 acres. The cultivar used in this field was Pioneer 0622Q Traite (corn), planted on April 28, 2022. Preplant sulfur application occurred on April 27, 2022, using gypsum (calcium sulfate). Harvest was completed on October 27, 2022. The farmer's sulfur rate (FSR) for this field was 30 lb S/ac.

The experimental design was a randomized complete block design with five sulfur (S) rates: 0, 10, 20, 30, and 40 lb S^{-1}ac (0, 11.2, 22.4, 33.6, and 44.8 kg^{-1}ha). These rates were chosen to cover a range from no application to potentially excessive application to identify the optimal rate in each field segment. Each block with five treatments was referred to as transects. Each sulfur rate was applied to plots within each transect, ensuring that all treatments were replicated multiple times within the field but without replication inside the blocks. The dimensions of the plots were approximately 70-80 feet (21.34-24.38 meters) wide and 150-600 feet (45.72/82.88 meters) long, depending on the applicator equipment used by the farmers.

Data Collection

The sulfur application was conducted using farmers' variable-rate technology, allowing precise application of the designated sulfur rates. After application, the farmers provided the raw sulfur application files (gypsum or ammonium sulfate). Yield data were collected in $lb^{-1}ac$ or $bushels^{-1}acre$ using a calibrated yield monitor on a combine harvester, which provided detailed yield measurements for each plot. Profitability in $dollars^{-1}acre$ was calculated using the farmer's corn price times the yield minus the fertilizer cost. Both sulfur and yield were cleaned using methods from Sudduth & Drummond (2007) in Python code or Yield Editor, a yield cleaning software developed by USDA-ARS Cropping Systems and Water Quality Unit in Columbia, MO. These methods involved filtering out erroneous data points and smoothing yield data to ensure accuracy and reliability.

Soil samples were collected by the farmers and their staff at a depth of 6 inches and provided for analysis of soil organic matter content. Soil type and texture data were obtained from the Soil Survey Geographic Database (SSURGO), an online platform developed and maintained by the National Resource Conservation Service (NRCS) of the United States Department of Agriculture (USDA).

After all the data were carefully collected, organized, and cleaned, QGIS (QGIS Development Team, 2021) was used for geospatial analysis and mapping of the study sites. This open-source Geographic Information System (GIS) software facilitated the design of the on-farm trials and management of agricultural geospatial data. Average values were used for sulfur and yield data when performing the spatial join to each study design grid, then exported in a .csv format readable by Microsoft Excel (Microsoft Corporation, 2019). Excel was employed for initial data entry, management, and further calculations of AOSR and EOSR. Then, further data and statistical analysis were performed using R software (R Core Team, 2021) in the RStudio integrated development environment (RStudio Team, 2021).

Statistical Analysis

Descriptive statistics were calculated to summarize each sulfur rate's yield and profitability data. A one-way Analysis of Variance (ANOVA) was conducted to determine the significance of sulfur rates on the corn crop yield. Post-hoc tests (Tukey's HSD) were used to identify specific differences between sulfur rates.

All statistical analyses were performed using R software (R Core Team, 2021) in the RStudio integrated development environment (RStudio Team, 2021). The significance level was set at $p < 0.05$ for all tests.

Calculation of AOSR and EOSR

The Agronomic Optimum Sulfur Rate (AOSR) was determined using Microsoft Excel. Each transect's sulfur rate that achieved the highest yield value was identified and assigned as the AOSR. This process involved examining the yield data for each sulfur rate and selecting the rate that maximized yield within each transect, thereby providing the highest agronomic benefit.

The Economic Optimum Sulfur Rate (EOSR) was calculated similarly. After determining the profitability for each sulfur rate, the sulfur rate that achieved the highest profitability in each transect was identified and assigned as the EOSR. This process involved analyzing the profitability data and selecting the sulfur rate that maximized economic returns within each transect, thus providing the highest economic benefit.

Results and discussion

Yield and Profit Response to Sulfur in Field A

The yield and profitability data analysis for Field A, as presented in Figure 2, reveals corn's response to varying sulfur application rates. The results indicate a positive correlation between sulfur rates and yield, although the differences among the treatment means are not statistically significant at the 95% confidence level ($p > 0.05$). The yields ranged from 203 $bu^{-1}ac$ at 0 lb $S^{-1}ac$

to 214 bu^{-1}ac at 40 lb S^{-1}ac, demonstrating an upward trend.

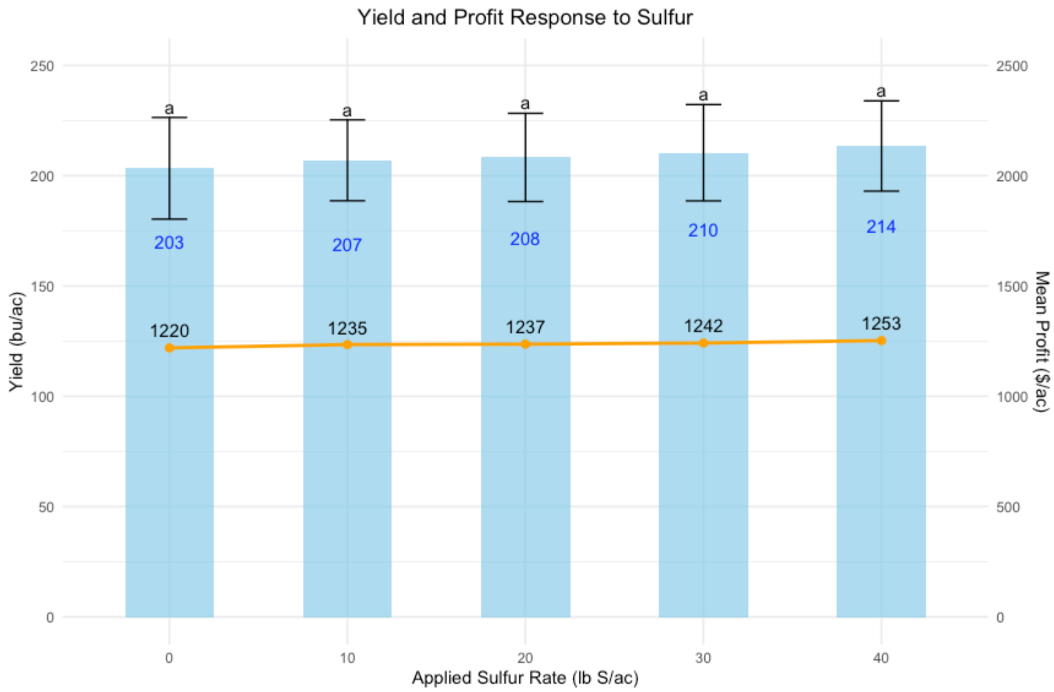

Figure 2. Yield and Profit Response to Sulfur in Field A. The figure displays the mean corn yield (bu^{-1}ac) and mean profit ($$^{-1}$ac) across varying sulfur application rates (0, 10, 20, 30, and 40 lb S^{-1}ac) for Field A.

Despite this positive trend, substantial variability within each treatment group is evident, as indicated by the error bars. The absence of statistically significant differences suggests that other variables in the field, such as soil heterogeneity, crop management practices, or environmental conditions, might have influenced the yield response.

AOSR and EOSR Variability Across Field A

The Agronomic Optimum Sulfur Rate (AOSR) and Economic Optimum Sulfur Rate (EOSR) maps (Table 1 and Figure 3) provide insights into the spatial variability of sulfur rate optimization within Field A.

Table 1 Agronomic and Economic Optimum Sulfur Rates (AOSR and EOSR) Across Field A area. The table presents the percentage of the field area requiring different sulfur rates to achieve AOSR and EOSR.

Target sulfur rate (lb S/ acre)	Percentages of the entire field where each target rate is optimal	
	Agronomically (%)	Economically (%)
0	19	31
10	6	6
20	19	13
30	19	19
40	38	31

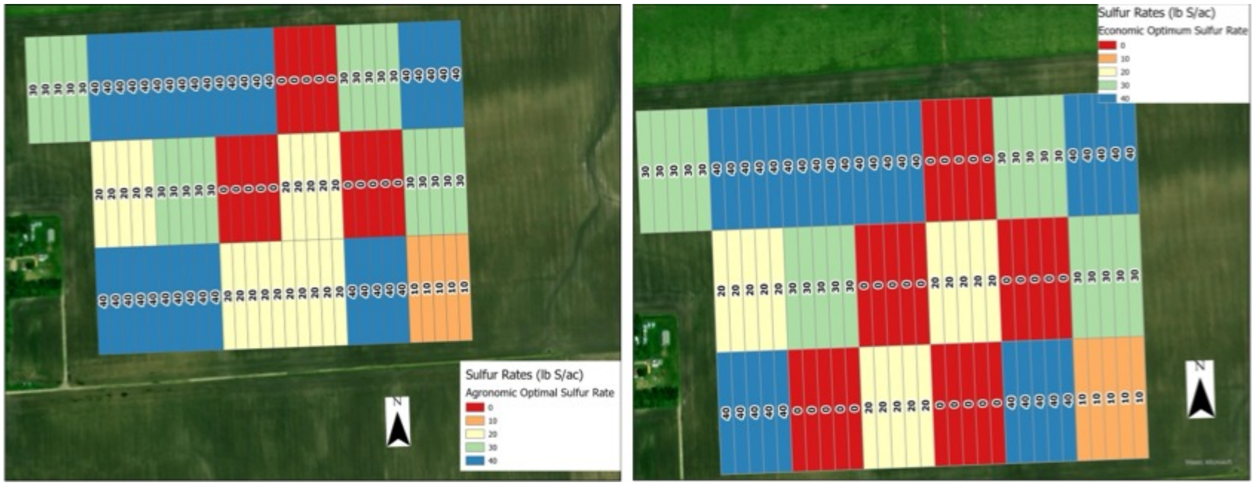

Figure 3. Spatial Distribution of Agronomic and Economic Optimum Sulfur Rates (AOSR and EOSR) in Field A. The left map (a) illustrates the spatial distribution of AOSR across field A, while the right map (b) shows the EOSR.

The AOSR map reveals that 40 lb S^{-1}ac was the optimal rate for agronomic performance across 38% of the field area, while 0 lb S^{-1}ac and 30 lb S^{-1}ac were each optimal for 19% of the area. Certain regions required 20 lb S^{-1}ac (19%) and 10 lb S^{-1}ac (6%), highlighting the spatial variability in soil fertility and sulfur availability. The EOSR map indicates that 0 lb S^{-1}ac and 40 lb S^{-1}ac were the most cost-effective rates for 31% of the field each, while 30 lb S^{-1}ac was optimal for 19% of the field area. This variability emphasizes the need for precision management to optimize agronomic and economic outcomes (Erickson and Fausti 2021; McBratney et al. 2000).

Soil Types and Organic Matter:

Field A consists of various soil types, varying from silt loam, very fine sandy loam, clay loam, silty clay loam, and loam. The organic matter content ranges from 1.7% to 2.8%, with a mean of 2.3%. The diversity in soil types and organic matter content likely contributed to the spatial variability observed in AOSR and EOSR. Soils with higher organic matter typically have more excellent nutrient retention and availability, which can influence the response to sulfur application. The variability in soil texture and organic matter across the field underscores the importance of site-specific nutrient management (De Lara et al. 2023; Miao et al. 2018).

Field A Result Discussion

The observed trends in yield and profit, combined with the spatial variability in AOSR and EOSR, indicate that variable-rate sulfur application positively influences corn production in Field A. However, the lack of statistically significant differences highlights the complexity of nutrient management in precision agriculture and extensive on-farm trials. Organic matter, moisture availability, and previous crop residues likely contributed to the variability in the sulfur response (Aula et al. 2019; Eriksen et al. 2004; Fleuridor et al. 2023; Kovar 2021).

The spatial variability in AOSR and EOSR accentuates the importance of precision sulfur management. By customizing sulfur application rates to specific field conditions, farmers can optimize both agronomic performance and economic returns. These findings highlight the potential benefits of precision sulfur fertilization while emphasizing the need for further research to explore the interaction effects of sulfur with other nutrients and environmental factors.

Yield and Profit Response to Sulfur in Field B

Field B's yield and profitability data analysis, depicted in Figure 4, reveals corn's response to varying sulfur application rates. The results indicate a modest correlation between sulfur rates and yield. However, the differences among the treatment means are not statistically significant at the 95% confidence level ($p>0.05$), as also occurred in Field A. The yield ranged from 150 bu^{-1}ac at 40 lb S^{-1}ac to 158 bu^{-1}ac at 10 lb S^{-1}ac, showing slight fluctuations without a clear upward or downward trend.

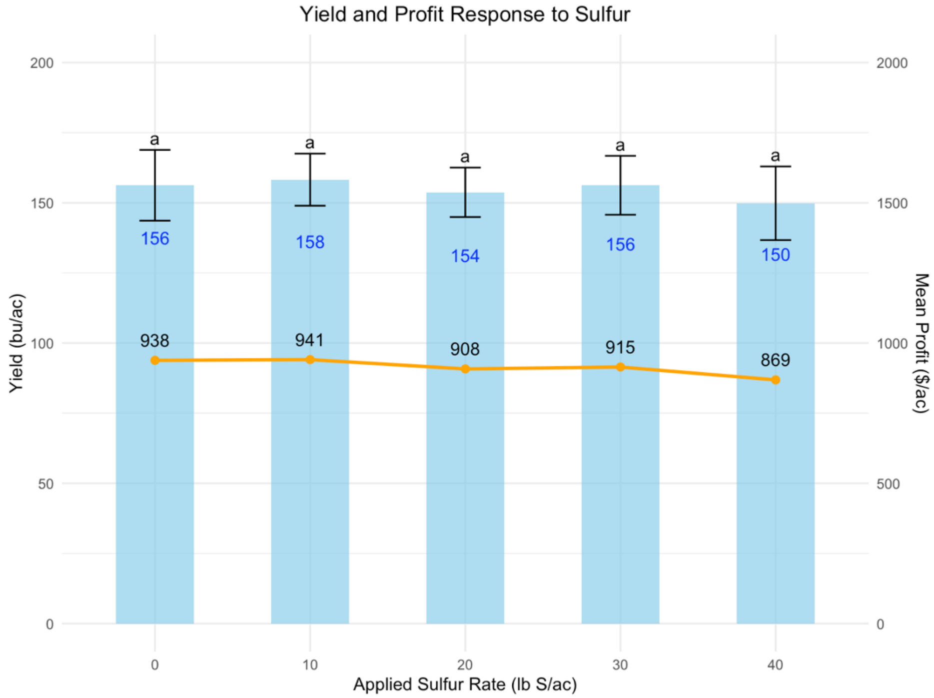

Figure 4. Yield and profit response to varying sulfur application rates in Field B. Letters above bars indicate no significant differences (Tukey's HSD test, p> 0.05)

The error bars indicate substantial variability within each treatment group despite the fluctuations. Again, there are no statistically significant differences, suggesting that other factors may have influenced the yield response.

AOSR and EOSR Variability Across Field B

The within-field variability maps of AOSR and EOSR maps (Table 2 and Figure 4) indicate the spatial distribution of sulfur response across Field B. As in Field A, there is no uniform optimal sulfur rate agronomically or economically across all fields. This information demonstrates the high variability and, therefore, the high potential of precision agriculture and variable-rate sulfur application in Field B.

Table 2 Agronomic and Economic Optimum Sulfur Rates (AOSR and EOSR) Across Field B area. The table presents the percentage of the field area requiring different sulfur rates to achieve AOSR and EOSR.

Target sulfur rate	Percentages of the entire field where each target rate is optimal	
(lb S/ acre)	Agronomically (%)	Economically (%)
0	17	17
10	39	39
20	0	0
30	22	22
40	22	22

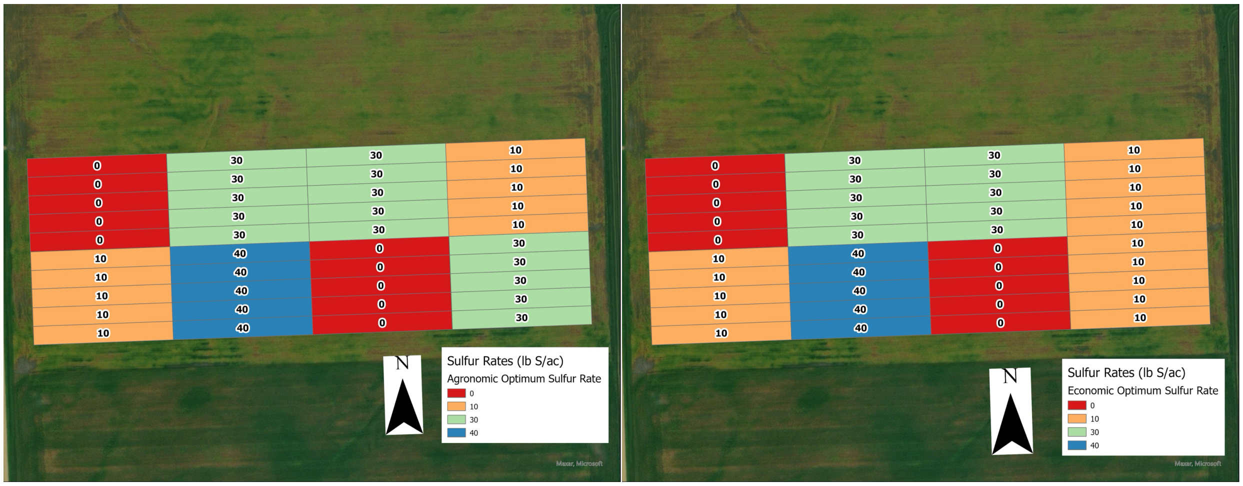

Figure 4. Spatial Distribution of Agronomic and Economic Optimum Sulfur Rates (AOSR and EOSR) in Field B. The left map (a) illustrates the spatial distribution of AOSR across field A, while the right map (b) shows the EOSR.

Field B Discussion:

The observed trends in yield and profit, combined with the statistical analysis, indicate that sulfur application did not significantly influence corn production in Field B. The absence of significant differences for the second field implies the complexity of nutrient management in on-farm trials; however, it also demonstrates a vast potential to explore using precision agriculture management techniques. As in Field A, factors such as soil organic matter, moisture availability, and previous crop residues likely contributed to the variability in sulfur response.

The soil types in Field B vary from loam, very fine sandy loam, silty clay loams, silt loam, clay loam, and loam, with slopes ranging from 0 to 3 percent. The organic matter content in the field varies from 4.6% to 5.8%. Higher organic matter content generally correlates with better nutrient retention and availability. This reason could have affected the sulfur response in Field B. However, the variability in soil types and organic matter across the field did not lead to significant differences in yield and profitability with varying sulfur rates.

Yield and Profit Response to Sulfur in Field C

The results of the field trials for Field C indicated that sulfur application did not significantly impact corn yield or profit. The ANOVA results show no significant differences between the sulfur rates ($p > 0.05$), confirming that sulfur application did not affect yield across the different treatments (Figure 5). The variability in yield between treatments was minimal, as indicated by the overlapping error bars and the lack of significant differences (all the groups are marked with an ‘a’ letter).

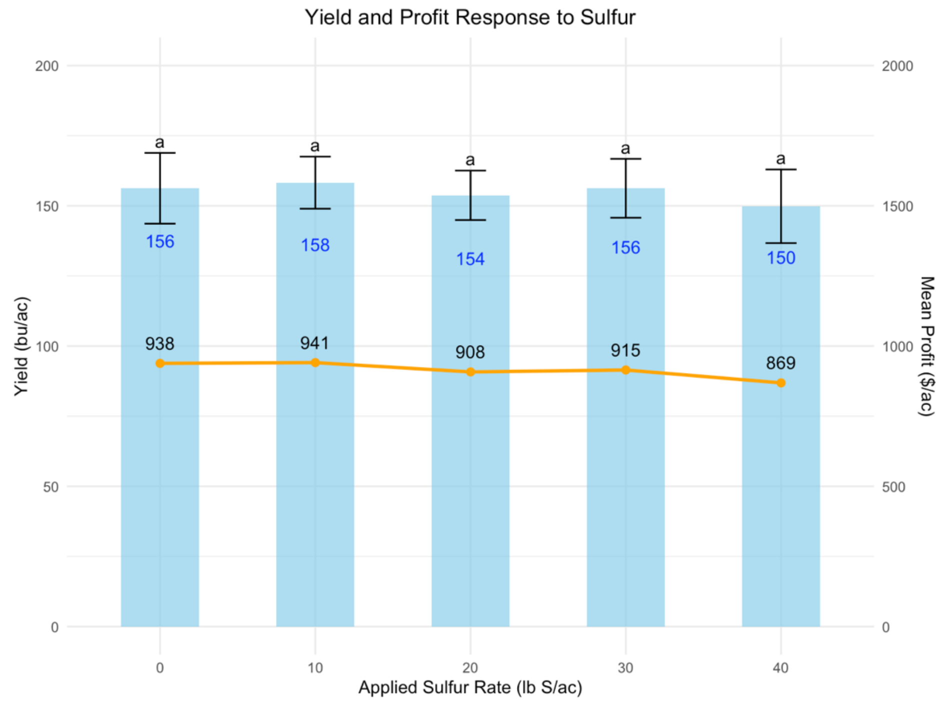

Figure 5. Yield and profit response to varying sulfur application rates in Field C. Letters above bars indicate no significant differences (Tukey's HSD test, p> 0.05)

AOSR and EOSR Variability Across Field C

The table and map showing the AOSR distribution (Table 3 and Figure 6) reveal that the 10 lb S^{-1}ac rate was optimal for the most significant portion of the field (37%), followed by the 20 lb S^{-1}ac (23%). The 0 lb S^{-1}ac rate was optimal for 21% of the field, suggesting that a significant portion did not require additional sulfur for maximum yield. The 30 lb S^{-1}ac and 40 lb S^{-1}ac rates were less frequently optimal, covering 10 %of the field.

The EOSR map (Figure 7 and Table 3) highlights the economic efficiency of different sulfur rates. The 10 lb S^{-1}ac rate was economically optimal for the most significant portion of the field (36%), followed closely by the 0 lb S^{-1}ac rate (34%). This suggests that no sulfur application was the most cost-effective strategy for a significant portion of the field. The 20 lb S^{-1}ac rate was optimal for 20% of the field, while the 30 lb S^{-1}ac and 40 lb S^{-1}ac rates were optimal for only 7% and 3% of the field, respectively.

Table 3 Agronomic and Economic Optimum Sulfur Rates (AOSR and EOSR) Across Field C area. The table presents the percentage of the field area requiring different sulfur rates to achieve AOSR and EOSR.

Target sulfur rate (lb S/ acre)	Percentages of the entire field where each target rate is optimal	
	Agronomically (%)	Economically (%)
0	21	34
10	37	36
20	23	20
30	10	7
40	10	3

Figure 6. Spatial Distribution of Agronomic and Economic Optimum Sulfur Rates (AOSR and EOSR) in Field C. The left map (a) illustrates the spatial distribution of AOSR across field A, while the correct map (b) shows the EOSR.

Impact of Soil Type and Organic Matter:

Field C had a variety of soil types and slopes, including loam, fine sandy loam, and sandy loam, with slopes varying from 2 to 6 percent in all of them. The organic matter content varied from m1.49% to 3.38%, with a mean of 2.44%.

The variability in soil types and organic matter influenced the distribution of AOSR and EOSR across the field. Areas with higher organic matter content and loamier soils tended to have lower optimal sulfur rates. For instance, the regions with high organic matter (3.38%) and fine sandy loam soils were optimal at lower sulfur rates or no additional sulfur.

Conclusion

This study provides a comprehensive evaluation of the within-field variability of sulfur response in corn production across three distinct fields in Minnesota in the year 2022. By assessing the yield and economic response to varying sulfur rates, we elucidated the critical role of precision agriculture in optimizing nutrient management.

In Field A, the yield responses varied minimally across sulfur rates, with the highest yield observed at 40 lb S^{-1}ac. However, profit analysis indicated diminishing returns with increasing sulfur rates, highlighting the need for economic considerations in sulfur management. Soil types and organic matter content significantly influenced the optimal sulfur rates. Areas with higher organic matter often required lower sulfur rates for optimal yield, demonstrating the importance of soil health in nutrient management.

In Field B, the yield responses were not significantly affected by varying sulfur rates, with the highest yield and profit observed at 10 lb S^{-1}ac. This suggests a threshold effect where additional sulfur beyond a certain point does not contribute to further yield benefits. The distribution of AOSR and EOSR mirrored the soil's capacity to supply sulfur, with regions of fine sandy loam and higher organic matter content requiring less sulfur. Precision sulfur management shows the potential to significantly reduce input costs without compromising yield.

For Field C, the situation was similar to the other fields; sulfur application did not significantly impact yield or profit, and 10 lb S^{-1}ac was frequently identified as the optimal rate. This indicates the efficiency of lower sulfur rates in achieving substantial yields. Variability in soil types and organic matter content was crucial in determining sulfur needs. Areas with higher organic matter and loamier soils exhibited lower optimal sulfur rates, reinforcing the importance of understanding soil properties for accurate sulfur applications.

The results from this study provide critical insights into implementing precision sulfur management strategies. By tailoring sulfur applications to the specific needs of different field zones, farmers can achieve optimal yields while minimizing input costs and environmental impact. The significant variability in AOSR and EOSR across fields underscores the importance of site-specific nutrient management, which can be facilitated through precision agriculture tools and approaches.

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