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Corn response to incremental applications of sulfate-sulfur

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Abstract

Reports of sulfur (S) deficiency symptoms in corn (*Zea mays* L.) fields of the Red River Valley of North Dakota and Minnesota are increasing. Current soil tests cannot predict the availability of S correctly due to the presence of gypsum in soils of this region. Field trials were conducted to determine corn yield and S uptake response to incremental applications of S (0, 11, 22, 33, and 44 kg S ha^{-1}) in the form of ammonium sulfate [$(NH_4)_2SO_4$]. Corn yield and S uptake varied significantly between sites. Out of 12 sites, only two sites had the highest corn yield without S application. Corn grain S removal ranged between 11 and 17 kg S ha^{-1} at harvest. Fertilizer-S (SO_4) application did not result in a significant yield response. The current recommendation of 11 kg S ha^{-1} may be necessary to reduce the risk of future S deficiency across this region and compensate for the removal of S in grain due to the uncertainty of adequate plant available S.

1 | INTRODUCTION

The United States is the largest producer of corn (*Zea mays* L.) in the world (USDA, 2018). A high level of production is important for the financial health of many farmers and to meet the feed grain demand of world livestock production (Ort & Long, 2014). In North Dakota, the area under corn production has steadily increased during the past few decades from 0.28 million ha in 1980 to more than 1.68 million hectares in 2018 (USDA, 2018). Average corn yield in the United States has increased from 3.9 Mg ha^{-1} in 1980 to 10.0 Mg ha^{-1} in 2018 (USDA, 2018). This increase in yield is due to the ongoing development of high-yielding hybrids and improved management practices (Grassini et al., 2011).

Nutrient management plays an important role in maximizing profitable corn production (Amanullah & Fageria et al., 2008; Fahad, 2018; Stewart & Roberts, 2012). Sulfur (S) is often considered the fourth essential nutrient for the optimum growth of plants. It is required for several plant functions, such as amino acid formation, which is the precursor of proteins and enzymes, and chlorophyll (Franzen & Grant, 2008). Unlike nitrogen (N), phosphorus (P), and potassium (K), S has not been studied extensively because S deficiency symptoms were not commonly present outside of very deep, low organic matter, sandy-textured soils (Rehm, 2005) until the past 20 yr. Another reason for increasing S deficiencies is the enactment of policies associated with the Clean Air Act of 1970, which has resulted in a series of regulations contributing to the reduction of S deposition from the air and rainfall (Dick et al., 2015). In the past, precipitation was an important S source and added a significant amount of S to soils (Andraski & Bundy, 1990). But due to reduced S air emissions resulting from regulating air quality, S additions from rainfall are much less, which has resulted in increasing S deficiency (Franzen, 2015). Additional reasons for the increase in S deficiency are increased yield and use of more concentrated phosphate fertilizers with fewer S contaminants (Scherer, 2001).

Because of increasing S deficiencies, many recent studies have been conducted to investigate the response of corn to S fertilizers. In Iowa, Lang et al. (2018) reported an increase in corn yield of 2.4 Mg ha^{-1} across five sites. In Iowa, 17 of 20

Abbreviations: MAP, monoammonium phosphate; SOM, soil organic matter.

fields in 2017 and 11 of 25 fields in 2008 showed a significant corn yield increase with S fertilization for soils with the previous history of S deficiency (Sawyer et al., 2011). On the contrary, Fawcett et al. (2016) found only 2 out of 12 sites showed corn grain yield response to S in Iowa. In the Red River Valley of North Dakota and Minnesota, Kaur et al. (2019) found corn yield increased with 11 kg S ha^{-1} at 2 of 10 sites in the 2016–2017 growing seasons. Kaiser et al. (2019) conducted two studies in Minnesota and found that the application of 8 kg S ha^{-1} increased hard red spring wheat (*Triticum aestivum* L.) yield on sandy soils. For soybean [*Glycine max* (L.) Merr.], yield increases of about 134 kg ha^{-1} across S fertilizer rates of 0–56 kg S ha^{-1} were reported across various soil series in Minnesota in 2011 and 2012 (Kruger et al., 2014). Application of gypsum ($CaSO_4$) at the rates of 16 kg S ha^{-1} and 67 kg S ha^{-1} increased the soybean yield by 4.8 and 11.6%, respectively, in Ohio. Application of gypsum at the rate of 16 kg S ha^{-1} increased the alfalfa (*Medicago sativa* L.) yield by 5% in 2001 and by 6% in 2002 (Chen et al., 2008).

In Nebraska, there was no response to applied S at all 11 sites with different soil textures. Wortmann et al. (2009) concluded that response to S was expected only in sandy textured soils, with soil organic matter (SOM) of more than 10 mg $kg^{-1,}$ which appeared to be adequate to fulfill plant S demand. One confounding factor in many studies is that irrigation water in the U.S. northern region typically contains enough S that no supplemental S is necessary (Olson & Rehm, 1986).

Soil tests of available S and SOM are not helpful to predict the probability of a positive S crop response, especially in the north-central region (Franzen, 2015). Many soils in this region contain high native gypsum deeper in the soil profile. The presence of gypsum in the soils can result in inaccurate soil test results and faulty diagnosis of S deficiencies (Franzen, 2018; Spencer & Freney, 1960). Similarly, Fixen (1990) found that soil tests were not beneficial for determining S fertilization needs because of extrinsic additions of S to the fields. In the north-central region of the United States, sulfate-S (SO_4–S) extraction with 500 mg/L mono-calcium phosphate is the most common method for SO_4–S analysis in the soil (Combs et al., 1998). However, the Ca^{+2} in the extracting solution can ion-pair or complex with the extracted SO_4–S to create a potential error in soil test S measurement. As an alternative soil analysis, paired plant tissue analysis from productive areas compared to relatively less productive areas within fields can be useful to diagnose S deficiency. Hence, with soil test uncertainty, we cannot be sure about the current recommendation for S application or predict the need for S fertilization in crops if they are guided by soil analysis. The current North Dakota recommendation for S application is 11–22 kg S ha^{-1} to obtain an optimal yield of corn (Franzen, 2018).

Field trials were conducted to evaluate the effect of S fertilization on corn in the Red River Valley of North Dakota and Minnesota during the 2018–2020 growing seasons. The objectives of this study are (a) to determine corn grain yield response to an incremental application of SO_4–S at the rate of 0, 11, 22, 33, and 44 kg ha^{-1} on soils of different series in the Red River Valley and (b) to determine corn S uptake at V6 growth stage and at maturity.

Core Ideas

- Corn grain yield and S uptake did not respond to a fertilizer-S application rate.
- Sulfur mineralization was enough to fulfill crop S demands.
- Soil organic matter content was not a reliable predictor for corn S response.

2 | MATERIALS AND METHODS

Corn yield response to S was examined at 12 sites in the Red River Valley of North Dakota and Minnesota during the 2018–2020 growing seasons. Soil series and texture information of experimental sites are presented in Table 1. Initial soil nutrient concentrations and basic soil physical–chemical properties are presented in Table 2. Rainfall and mean air temperature data are given in Tables 3 and 4, respectively. Weather data was collected from the closest weather stations to each site associated with the North Dakota Agricultural Weather Network for each growing season (NDAWN, http://ndawn.ndsu.nodak.edu/).

2.1 | Field experiment

Five SO_4–S rates at the rate of 0, 11, 22, 33, and 44 kg S ha^{-1} in the form of ammonium sulfate $(NH_4)_2SO_4$ were arranged in a randomized complete block design with four replications. Fertilizers were broadcasted by hand and incorporated to a 10-cm depth using a field cultivator operated at 10 km h^{-1} before planting corn in May. The experimental plot length and width were 7.60 and 3.35 m, respectively. The inter-row spacing was 0.56 m with six rows within the experimental plot at all sites except at Walcott I and Walcott II, where it was 0.76 m with four rows within the experimental plot. DKC35-88RIB cultivar of corn was planted at a seeding rate of 85,000 plants ha^{-1}. Roundup Max (a.i. Isopropylamine salt of glyphosate; Bayer CropScience) at a rate of 25 ml L^{-1} was applied at the V8 growth stage once to control weeds. In 2020, Laudis (a.i. Tembotrione: 2-[2-chloro-4-(methylsulfonyl)−3-[(2,2,2-trifluoroethoxy) methyl] benzoyl]−1,3-cyclohexanedione; Bayer CropScience) was applied at V6 growth stage once to control weeds. Fertilizer phosphorus (P), and potassium (K) were applied according

TABLE 1 Soil series and texture information of 12 experimental sites selected in 2018–2020 growing seasons

Site	Soil Series	Taxonomic classification[a]
Ada I	Augsburg sandy loam	coarse-silty over clayey, mixed over smectitic, superactive, frigid Typic Calciaquoll
Walcott I	Bearden silt loam	fine-silty, mixed, superactive, frigid Aeric Calciaquoll
Amenia I	Glyndon sandy loam	coarse-silty, mixed, superactive, frigid Aeric Calciaquoll
Sabin	Lamoure sandy loam	fine-silty, mixed, superactive, calcareous, frigid Cumulic Endoaquoll
Casselton	Bearden clay loam	fine-silty, mixed, superactive, frigid Aeric Calciaquoll
Ada II	Augsburg sandy loam	coarse-silty over clayey, mixed over smectitic, superactive, frigid Typic Calciaquoll
Walcott II	Bearden silt loam	fine-silty, mixed, superactive, frigid Aeric Calciaquoll
Amenia II	Glyndon sandy loam	coarse-silty, mixed, superactive, frigid Aeric Calciaquoll
Downer	Wyndmere loamy sand	coarse-loamy, mixed, superactive, frigid Aeric Calciaquoll
Chaffee I	Glyndon sandy loam	coarse-silty, mixed, superactive, frigid Aeric Calciaquoll
Chaffee II	Glyndon sandy loam	coarse-silty, mixed, superactive, frigid Aeric Calciaquoll
Wheatland	Bearden clay loam	fine-silty, mixed, superactive, frigid Aeric Calciaquoll

[a]*Source*: Web soil survey (https://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx).

TABLE 2 Geographical locations and soil test information of 12 experimental sites selected in the 2018–2020 growing seasons

Site	Latitude and Longitude	Planting date	Previous crop	Olsen-P	K	pH	EC	OM	NO_3–N[a]	SO_4–S
				mg kg^{-1}		1:1	dS m^{-1}	g kg^{-1}	kg ha^{-1}	mg kg^{-1}
				2018						
Ada I	47°19′41.9“ N, 96°23′48.5″ W	14 May	spring wheat	5	67	8.5	0.48	24	20	18
Walcott I	46°30′52.4“ N, 96°52′04.3″ W	18 May	soybean	3	188	8.0	1.76	39	22	13
Amenia I	46°59′05.7“ N, 97°14′26.1″ W	4 May	soybean	5	385	8.0	0.96	48	24	10
Sabin	46°51′52.2“ N, 96°31′5.80″ W	2 May	soybean	7	89	8.7	0.34	21	11	19
Casselton	46°56′52.2“ N, 96°31′5.80″ W	1 May	soybean	11	253	7.4	0.48	49	39	7
				2019						
Ada II	47°18′36.9“ N, 96°23′26.5″W	8 May	spring wheat	8	93	8.3	1.19	35	22	15
Walcott II	46°31′45.2“ N, 96°54′14.3″ W	12 May	soybean	3	256	8.0	2.17	47	27	14
Amenia II	46°59′05.9″ N 97°14′26.4″ W	10 May	soybean	8	210	8.2	0.80	51	23	9
Downer	46°46′21.4″ N 96°32′53.7″ W	15 May	sugar beet(*Beta vulgaris* L.)	11	70	7.5	0.68	35	25	16
Chaffee I	46°42′40.3″ N 97°19′30.3″ W	1 May	sugar beet	11	193	7.9	0.53	42	28	11
				2020						
Chaffee II	46°41′47.3″ N 97°19′29.6″ W	26 April	sugar beet	6	96	8.6	0.30	12	22	22
Wheatland	46°59′30.2″ N 97°20′00.9″ W	31 May	soybean	4	118	8.0	1.23	32	40	8

Note. EC, electrical conductivity; OM, organic matter.
[a]NO_3–N and SO_4–S from 0 to 60 cm, all other properties were determined from 0 to15 cm.

TABLE 3 Total rainfall (mm) and departure from normal (1981–2010) (DN) for each site

Site	May Total	May DN	June Total	June DN	July Total	July DN	Aug. Total	Aug. DN	Sept. Total	Sept. DN	Oct. Total	Oct. DN	Total Precipitation	DN
					2018									
Ada I	62.7	–19.6	78.2	–35.6	62.5	–30.7	66.6	–3.00	73.7	6.70	80.0	23.1	424	–59.1
Walcott I	22.1	–54.6	95.0	2.30	107	24.4	96.0	33.3	38.6	–24.9	46.2	–7.10	405	–26.6
Amenia I	53.9	–23.7	79.3	–21.0	65.3	–22.6	78.5	11.9	70.9	5.36	66.6	4.87	415	–45.2
Sabin	13.8	–66.4	148	43.1	117	35.5	91.9	24.1	63.0	–11.7	70.9	4.86	505	29.5
Casselton	53.9	–23.7	79.3	–21.0	65.3	–22.6	78.5	11.9	70.9	5.36	66.6	4.87	415	–45.2
					2019									
Ada II	62.4	–19.9	68.3	–45.5	103	9.78	93.7	24.1	106	38.9	92.2	35.3	526	42.9
Walcott II	71.6	–5.10	67.3	–25.4	160	77.4	63.5	0.76	147	83.5	69.3	15.9	579	147
Amenia II	59.9	–17.5	121	20.7	156	68.1	102	35.4	147	81.5	76.9	15.2	663	203
Downer	62.4	–19.9	68.3	–45.5	103	9.78	93.7	24.1	106	38.9	92.2	35.3	526	42.7
Chaffee I	59.9	–17.5	121	20.7	156	68.1	102	35.4	147	81.5	76.9	15.2	663	203
					2020									
Chaffee II	22.1	–54.6	75.7	–17.0	161	78.3	116	52.9	16.5	–47.0	9.90	–43.4	401	–30.8
Wheatland	41.1	–36.3	79.0	–21.3	122	34.9	116	49.1	13.2	–52.3	7.60	–54.1	379	–80.0

TABLE 4 Average air temperature (˚C) and departure from normal (1981–2010) (DN) for each site

Site	May Avg.	May DN	June Avg.	June DN	July Avg.	July DN	Aug. Avg.	Aug. DN	Sept. Avg.	Sept. DN	Oct. Avg.	Oct. DN
					2018							
Ada I	16.7	3.47	20.6	2.06	20.6	–0.40	19.4	–0.85	13.3	–1.24	3.90	–2.91
Walcott I	17.2	3.25	20.6	1.54	20.6	–1.03	19.4	–1.15	13.9	–1.32	3.90	–3.80
Amenia I	16.7	3.26	20.6	1.92	20	–1.30	19.4	–0.98	13.9	–0.92	3.90	–3.39
Sabin	17.8	3.49	21.1	1.82	21.1	–0.9	19.4	–1.79	14.4	–1.07	4.40	–3.07
Casselton	16.7	3.26	20.6	1.92	20	–1.30	19.4	–0.98	13.9	–0.92	3.90	–3.39
					2019							
Ada II	11.1	–2.12	18.3	–0.24	21.1	0.09	18.3	–1.95	15.0	0.46	5.00	–1.81
Walcott II	11.1	–2.84	19.4	0.34	21.7	0.07	18.9	–1.65	16.1	0.87	5.00	–2.07
Amenia II	10.6	–2.83	18.9	0.22	21.7	0.39	18.3	–2.08	15.6	0.78	4.40	–2.89
Downer	11.1	–2.12	18.3	–0.24	21.1	0.09	18.3	–1.95	15.0	0.46	5.00	–1.81
Chaffee I	10.6	–2.83	18.9	0.22	21.7	0.39	18.3	–2.08	15.6	0.78	4.40	–2.89
					2020							
Chaffee II	11.9	–3.77	21.4	4.16	22.2	1.01	20.0	–1.05	13.9	–2.39	3.20	–8.09
Wheatland	12.0	–2.61	21.3	4.79	22.1	1.46	20.4	–0.03	14.1	–1.37	3.40	–7.01

to the North Dakota Fertilizer recommendation Tables and Equations (Franzen, 2018). Monoammonium phosphate (MAP, 11–52–0) was used to supply P at a rate of 70 kg ha^{-1} at Ada, Sabin, Casselton, and Amenia and at a rate of 92 kg ha^{-1} at the Walcott site in 2018. In 2019, MAP was applied at a rate of 45 kg ha^{-1} at Ada, Amenia, Downer, and Chaffee and a rate of 92 kg ha^{-1} at Walcott. During the 2020 growing season, MAP was applied at the rate of 70 kg ha^{-1} at Chaffee and Wheatland. Muriate of potash (MOP, 0–0–60) was used to supply K at a rate of 80 kg K_2O ha^{-1} at all the sites. Urea was used to supply N at a rate of 180 kg ha^{-1}. The N fertilizer application rate was adjusted to the 180 kg N ha^{-1} rate, with consideration of N supply from residual soil N, N supplied from the MAP rate, and the N contained in different S application rates. Corn was harvested in October in all years.

2.2 | Soil analyses

Soil samples were collected before fertilizer application in May at a depth of 0–15 cm and 15–60 cm during the 2018–2020 growing seasons. Soil samples were air-dried and ground to pass through a 2-mm sieve. Soil samples collected within 0–15 cm depth were analyzed for pH (1:1 soil/water) (Watson & Brown, 1998), electrical conductivity (Whitney, 1998), soil particle size distribution (Gee & Bouder, 1986), SOM content by loss on ignition at 360 ˚C (Combs & Nathan, 1998), plant available P index using the Olsen method (Frank et al., 1998), and plant available K index using 1-M ammonium acetate extraction (Warncke & Brown, 1998). Soil from each depth was extracted with 2 M potassium chloride (KCl) and analyzed for nitrate-N (NO_3–N) concentration (Gelderman & Beegle, 1998) and monocalcium phosphate for extractable SO_4–S (Combs et al., 1998). In-season soil samples were collected at the V6 crop growth stage at a depth of 0–30 cm and were analyzed for available S. Ten grams of soil sample was extracted with 25 ml of monocalcium phosphate using charcoal to obtain clear filtrate and analyzed for S concentration using inductively coupled plasma emission spectroscopy (ICP) (Thermo Scientific-ICAP 6500, Thermo Fisher Scientific).

2.3 | Plant sampling

Five random corn samples per plot were collected from each experimental site at the V6 growth stage and again at the harvest of corn. The plants at V6 were cut off at the soil surface from rows not intended for grain harvest. The plants without grain and cob at maturity were also cut off at the soil surface and were located in rows not intended for grain harvest. Plant samples were dried at 60 ˚C and then ground to pass through a 2-mm sieve. One-half gram of plant material was digested with 20 ml of concentrated nitric acid (Soltanpour & Havlin, 1980) and analyzed for S concentration using inductively coupled plasma emission spectroscopy. Sulfur uptake was calculated by the following equation.

$$\text{S uptake}\left(\text{kg ha}^{-1}\right) = \text{no. of plants}\left(\text{ha}^{-1}\right) \times \text{average dry weight of five plant (kg)} \times \text{concentration of S}\left(\text{mg kg}^{-1}\right)/10^6 \quad (1)$$

2.4 | Corn grain yield determination

The middle two rows from each experimental plot were hand-harvested to estimate the yield for all the sites during the 2018–2020 growing seasons. Grain moisture and test weight were measured using Dickey John Grain Moisture tester (GAC 500 XT). Grain was dried at 60 ˚C and yields were adjusted after shelling and weighing to 155 g kg^{-1} moisture. The yield was calculated using the following equation.

$$\text{Corn yield}\left(\text{kg ha}^{-1}\right) = \text{Weight of harvested corn (kg)} \times 10{,}000\ \text{m}^2/\text{length of the row (m)} \times \text{width of the row (m)} \times (100 - \text{grain moisture percentage})/84.5 \quad (2)$$

2.5 | Statistical analysis

An overall ANOVA was performed using the PROC MIXED procedure in Statistical Analysis System 9.4 (SAS Institute, Inc.) for evaluating the site, year, treatment (S rate), and their interactions on corn yield and S uptake. Significant differences were determined at .05 level using an LSD procedure within SAS.

3 | RESULTS

3.1 | Location characteristics

Textural class and initial soil nutrient availability are presented in Tables 1 and 2, respectively. Plant available P index varied across all the sites; out of 12 sites, 2 sites, Walcott I and Walcott II, tested very low (0–3 mg kg^{-1}); five sites (Ada I, Amenia I, Sabin, Chaffee II, and Wheatland) were low (4–7 mg kg^{-1}); and the remaining five sites (Casselton, Ada II, Amenia II, Downer, and Chaffee I) tested medium (8–11 mg kg^{-1}). Plant available K index tested low for at Ada I and Downer (41–80 mg kg^{-1}), medium for four sites (Sabin, Ada II, Chaffee II, and Wheatland) (81–120 mg kg^{-1}), and very high for the remaining six sites (Walcott I, Amenia I, Casselton, Walcott II, Amenia II, and Chaffee I) (>151 mg kg^{-1}). Three sites tested relatively low in SOM (10–30 g kg^{-1}), four sites (Ada I, Sabin, Chaffee II, and Wheatland) tested medium in SOM (30–40 g kg^{-1}), and eight sites (Walcott I, Amenia I, Casselton, Ada II, Walcott II, Amenia II, Downer, and Chaffee I) tested very high (>40 g kg^{-1}). Initial extractable nitrate-N (NO_3–N) and sulfate-S (SO_4–S) within 0-to-15-cm soil depth ranged from 11 to 40 kg ha^{-1} and 7 to 22 mg kg^{-1}, respectively.

Total monthly precipitation and average air temperature for the 12 experimental sites during the 2018–2020 growing seasons are presented in Tables 3 and 4, respectively. The cumulative rainfall from May through October was greater in 2019 (2,957 mm) as compared to 2018 (2,164 mm) and 2020 (780 mm) at all sites. In 2018, all sites received less cumulative rainfall than the 30-yr normal (1981–2010) except for Sabin. Sabin received 29.5 mm more cumulative rainfall from May through October than normal, whereas Ada I, Walcott I, Amenia I, and Casselton received 59.1, 26.6, 45.2, and

TABLE 5 Analysis of variance for grain yield, S uptake at V6 stage, stover S uptake at maturity, grain S uptake, and total (stover + grain) S uptake at maturity at each site during the 2018–2020 growing seasons

Source of variation	Grain yield	S uptake at V6 stage	Stover S uptake at maturity	Grain S uptake	Grain + Stalk
	p value				
Site	<.0001*	<.0001*	<.0001*	<.0001*	<.0001*
Year	<.0001*	<.0001*	.03*	NS	NS
Treatment	NS	NS	NS	NS	NS
Site x Year	<.0001*	<.0001*	<.0001*	<.0001*	NS
Year x Treatment	NS	NS	NS	NS	NS
Site x Treatment	NS	.02*	NS	NS	NS
Site x Year x Treatment	NS	NS	NS	NS	NS

Note. NS = non-significant.
*Significant at .05 probability level.

45.2 mm less than the normal, respectively. In 2018, all sites were drier than normal in May, and most of the precipitation occurred in August except for Ada I and Sabin. In 2019, the cumulative rainfall from May through October for all sites was much greater than the 30-yr normal rainfall. The actual annual rainfall was 42.9, 147, 203, 42.7, and 203 mm more than normal for Ada II, Walcott II, Amenia II, Downer, and Chaffee I, respectively. In 2019, a dry period occurred in May at all the sites, while most of the rainfall occurred in September. In 2020, the cumulative rainfall from May through October for all the sites was also much less than the 30-yr normal rainfall. The actual annual rainfall was 30.8 and 80.0 mm less than the normal rainfall for the sites Chaffee II and Wheatland, respectively.

3.2 | Corn grain yield

Growing season, site, and their interaction affected corn grain yield; however, grain yield was not affected by S application rates and its interactions with year and site (Table 5). Across three growing years, corn grain yield was significantly greater in 2019 (15.4 Mg ha^{-1}) than in 2018 (14.5 Mg ha^{-1}) and 2020 (12.8 Mg ha^{-1}) (Table 6). Across 12 site-year, Walcott II in 2019 had the greatest average site yield (19.8 Mg ha^{-1}), and the lowest yield of 11.3 Mg ha^{-1} was recorded at Amenia I in 2018. The S application had no significant effect on grain yield across 12 site-year.

3.3 | Sulfur uptake at V6 stage

Sulfur uptake at V6 stage was significantly influenced by site, year, site × year, and site × S treatment; however, S treatment had no significant effect (Table 5). Over 2 yr, the 2019 growing season had higher S uptake (1.73 kg ha^{-1}) at V6 than in 2020 (1.00 kg ha^{-1}). Based on site-average, Chaffee I, in 2019, had the highest V6-S uptake (3.26 kg ha^{-1}), significantly higher than the rest of the sites, and the lowest was observed at Ada II in 2019 (0.71 kg ha^{-1}) (Table 7). Comparing S uptake in 2019 and 2020, the S uptake in 2019 had greater S uptake at V6 than 2020. Based on site-year, Chaffee I in 2019 had the greatest uptake, compared to the other sites. In 2019, average S uptake had the following sequence: Chaffee I > Walcott II > Amenia II > Downer > Ada II. In 2020, Chaffee II and Wheatland did not differ in S uptake at V6.

3.4 | Stover S uptake at maturity

The site, year, and their interaction had a significant effect on stover-S uptake at maturity (Table 5). S-treatment had no effect on S uptake. Average stover-S uptake was higher in 2020 than in 2019 (Table 8). Across 7 site-years, Wheatland, in 2020, had the highest stover-S uptake (average of all S-treatments) significantly greater than average stover S uptake of Chaffee II site. Within 2019, Walcott II, Amenia II, Ada II, and Downer had similar stover S uptake, and Chaffee I had the lowest stover S uptake, significantly lower than the rest of the sites. Stover S uptake ranged between 4.05 and 8.96 kg S ha^{-1}. For all seven sites, the highest S uptake was recorded in a treatment receiving S, not the control, but the increase in stover S uptake was inconsistent over S rates and was not significant at the 95% level.

3.5 | Grain S uptake

Grain S uptake was only influenced by the site and its interaction with a year (Table 5). In 2019, Walcott II had the highest grain S uptake, significantly higher than the rest of the four sites (Table 9). Downer had the lowest grain S uptake, similar to Ada II and Chaffee I. Grain S uptake ranged between 11.1 and 17.7 kg S ha^{-1}.

TABLE 6 Corn grain yield (Mg ha^{-1}) in response to an incremental application of sulfur (SO_4–S kg ha^{-1}) at each site during the 2018–2020 growing seasons. Values in parentheses are standard deviation of mean

	2018						2019						2020		
Treatment	Ada I	Walcott I	Amenia I	Sabin	Casselton	Mean	Ada II	Walcott II	Amenia II	Downer	Chaffee I	Mean	Chaffee II	Wheatland	Mean
SO_4–S kg ha^{-1}	Mg ha^{-1}														
0	17.3 (1.28)	16.0 (0.68)	12.2 (0.98)	14.5 (0.96)	14.9 (1.72)	15.0 (1.12)	14.0 (0.54)	19.2 (1.80)	13.9 (1.85)	14.2 (0.53)	12.3 (1.69)	14.7 (1.28)	13.8 (1.20)	12.4 (0.73)	13.1 (0.97)
11	16.3 (0.71)	17.0 (0.67)	12.4 (1.31)	14.4 (0.40)	13.1 (0.76)	14.6 (0.77)	14.9 (1.60)	19.1 (1.51)	14.9 (1.19)	14.8 (1.24)	12.7 (1.15)	15.3 (1.34)	14.0 (3.71)	10.4 (2.61)	12.2 (3.16)
22	16.2 (0.72)	17.0 (0.71)	10.9 (1.08)	12.6 (2.13)	14.3 (1.37)	14.2 (1.20)	13.6 (0.53)	20.4 (0.49)	14.7 (1.15)	15.2 (1.02)	13.7 (0.31)	15.5 (0.70)	15.0 (1.65)	12.5 (1.16)	13.7 (1.41)
33	17.7 (0.77)	16.2 (0.43)	10.3 (0.61)	13.3 (1.95)	12.1 (1.73)	13.9 (1.10)	14.6 (0.76)	21.6 (1.30)	15.5 (0.82)	14.1 (0.38)	13.6 (0.93)	15.9 (0.84)	13.5 (1.76)	11.3 (2.72)	12.4 (2.24)
44	17.0 (0.75)	17.1 (0.36)	10.7 (1.51)	13.9 (1.08)	13.3 (1.21)	14.4 (0.98)	14.3 (1.01)	18.7 (1.08)	16.0 (1.70)	14.4 (0.81)	12.9 (1.60)	15.3 (1.24)	13.3 (1.70)	11.1 (1.96)	12.2 (1.83)
Mean	16.9 b[a] (0.85)	16.7 b (0.57)	11.3 g (1.10)	13.7 ef (1.30)	13.5 ef (1.36)	14.4 (1.04)	14.3 ecd (0.89)	19.8 a (1.23)	15.0 c (1.34)	14.6 cd (0.80)	13.1 f (1.14)	15.3 (1.08)	13.9 ed (2.00)	11.5 g (1.84)	12.7 (1.92)
Annual	14.4 (1.04) B[b]						15.3 (1.08) A						12.7 (1.92) C		

[a]Means with different lowercase letters are significantly different for five S application rates at P≤ .05

[b]Means with different capital letters are significantly different for three growing seasons at $P \leq .05$ by the LSD test.

TABLE 7 Sulfur uptake (kg ha^{-1}) at V6 stage of corn growth in response to an incremental application of sulfur (SO_4–S kg ha^{-1}) at seven sites during the 2019–2020 growing seasons. Values in parentheses present the standard deviation value of mean

	2019							2020	
Treatment	**Ada II**	**Walcott II**	**Amenia II**	**Downer**	**Chaffee I**	**Mean**	**Chaffee II**	**Wheatland**	**Mean**
SO_4–S kg ha^{-1}	kg ha^{-1}								
0	0.67 (0.07) a[a]	2.05 (0.34) bc	1.28 (0.21) defg	0.99 (0.15) adef	3.65 (1.00) h	1.73 (0.35)	0.77 (0.30) ad	0.99 (0.23) adef	0.88 (0.27)
11	0.69 (0.08) a	2.16 (0.27) b	1.44 (0.42) efg	0.86 (0.14) ad	3.71 (0.82) h	1.77 (0.35)	0.98 (0.40) adef	1.03 (0.26) adef	1.01 (0.33)
22	0.75 (0.15) a	2.27 (0.52) b	1.40 (0.17) efg	1.01 (0.26) adef	3.42(1.09) hi	1.77 (0.44)	1.17(0.21) adefg	1.20 (0.26) adefg	1.19 (0.24)
33	0.69 (0.09) a	2.28 (0.48) b	1.49 (0.21) fg	1.11(0.16) adef	3.12 (0.56) i	1.74 (0.30)	0.94 (0.22) ade	0.81 (0.30) ad	0.88 (0.26)
44	0.73 (0.08) a	2.46 (0.35) b	1.64 (0.10) cg	1.03 (0.09) adef	2.42 (0.08) b	1.66 (0.14)	1.38 (0.50) efg	0.75 (0.23) a	1.07 (0.37)
Mean	0.71 (0.09) e	2.24 (0.39) b	1.45 (0.22) c	1.00 (0.16) d	3.26 (0.71) a	1.73 (0.32)	1.05 (0.33) d	0.96 (0.26) de	1.00 (0.29)
Annual	1.73 (0.32) A[b]							1.00 B	

[a]Means with different lowercase letters are significantly different for the same site at $P \leq .05$ by the LSD test.

[b]Means with different uppercase letters are significantly different between two growing seasons at $P \leq .05$ by the LSD test.

TABLE 8 Stover sulfur uptake (kg ha^{-1}) at maturity of corn in response to an incremental application of sulfur (SO_4–S kg ha^{-1}) at seven sites during the 2019–2020 growing seasons. Values in parentheses present the standard deviation value of mean

	2019						2020		
Treatment	Ada II	Walcott II	Amenia II	Downer	Chaffee I	Mean	Chaffee II	Wheatland	Mean
SO_4–S kg ha^{-1}	kg ha^{-1}								
0	5.77 (1.60)	5.68 (0.72)	6.07 (0.95)	6.06 (0.96)	4.05 (0.75)	5.53 (1.00)	4.24 (0.65)	8.14 (0.42)	6.19 (0.54)
11	5.54 (1.93)	6.74 (0.91)	5.29 (1.03)	5.42 (1.08)	4.10 (0.94)	5.42 (1.18)	4.98 (0.55)	8.96 (2.27)	6.97 (1.41)
22	6.25 (1.76)	6.40 (0.82)	5.79 (1.08)	6.31 (1.27)	3.99 (1.16)	5.80 (1.22)	4.76 (1.31)	6.60 (1.53)	5.68 (1.42)
33	5.69 (1.71)	5.95 (0.74)	6.20 (0.77)	6.84 (2.17)	4.00 (1.36)	5.74 (1.35)	5.51 (0.66)	8.83 (1.06)	7.17 (0.86)
44	6.34 (2.22)	5.96 (0.47)	7.37 (1.21)	5.84 (0.80)	4.42 (0.34)	5.99 (1.01)	6.02 (0.90)	8.19 (1.34)	7.11 (1.12)
Mean	5.97 (1.84) b[a]	6.15 (0.73) b	6.14 (1.01) b	6.09 (1.26) b	4.11(0.91) d	5.69 (1.15)	5.10 (0.81) c	8.14 (1.32) a	6.62 (1.07)
Annual	5.69 (1.15) B[b]						6.62 (1.07) A		

[a]Means with different lowercase letters are significantly different for the same site at $P \leq .05$ by the LSD test.
[b]Means with different uppercase letters are significantly different between two growing seasons at $P \leq .05$ by the LSD test.

TABLE 9 Grain sulfur uptake (kg ha^{-1}) in response to an incremental application of sulfur (SO_4–S kg ha^{-1}) at seven sites during the 2019–2020 growing seasons. Values in parentheses present the standard deviation value of mean

	2019						2020		
Treatment	Ada II	Walcott II	Amenia II	Downer	Chaffee I	Mean	Chaffee II	Wheatland	Mean
SO_4–S kg ha^{-1}	kg ha^{-1}								
kg 0	12.0 (0.63)	17.0 (2.91)	12.0 (1.38)	11.0 (0.08)	11.3 (1.84)	12.7 (1.37)	15.7 (5.60)	15.5 (2.28)	15.6 (3.94)
11	12.5 (1.91)	16.9 (0.34)	13.3 (0.75)	11.7 (1.50)	11.4 (1.22)	13.2 (1.14)	14.0 (3.56)	12.9 (3.61)	13.4 (3.59)
22	12.1 (0.52)	17.7 (1.33)	13.2 (1.76)	12.2 (0.99)	11.9 (0.61)	13.4 (1.04)	15.5 (3.71)	15.6 (2.00)	15.6 (2.86)
33	12.3 (1.14)	17.2 (1.63)	13.6 (0.88)	11.1 (0.33)	12.0 (1.61)	13.2 (1.12)	13.1 (0.76)	13.5 (3.26)	13.3 (2.01)
44	12.1 (0.66)	17.0 (0.42)	14.4 (1.62)	11.9 (0.90)	11.5 (1.52)	13.4 (1.02)	12.9 (2.43)	14.2 (2.91)	13.6 (2.67)
Mean	12.2 (0.97) cd[a]	17.1 (1.33) a	13.3 (1.28) bc	11.6 (0.76) d	11.6 (1.36) d	13.2 (1.14)	14.3 (3.21) b	14.3 (2.81) b	14.3 (3.01)
Annual	13.2 (1.14)						14.3 (3.01)		

[a]Means with different lowercase letters are significantly different for the same site at $P \leq .05$ by the LSD test.

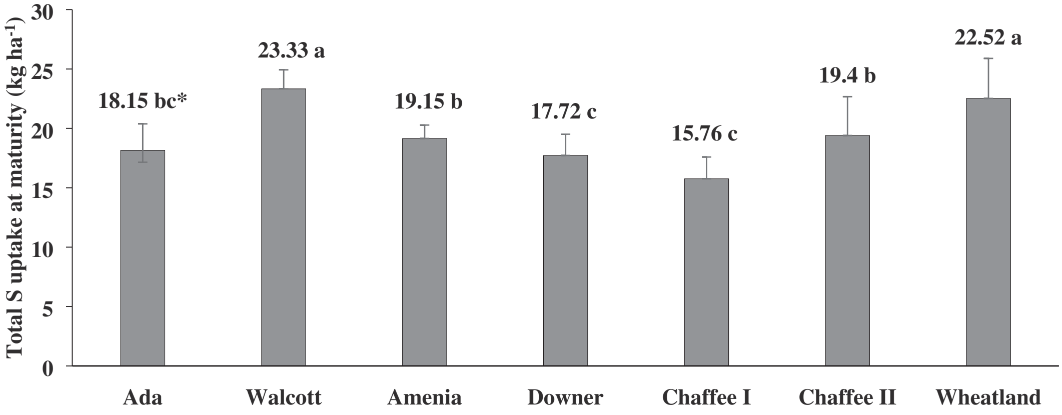

FIGURE 1 Mean total (stover + grain) sulfur (S) uptake (kg ha^{-1}) at physiological maturity averaged across sites during 2019 and 2020 growing seasons. *Different small letters indicate significant differences at 95% significance level

3.6 | Total (stover + grain) S uptake at maturity

Total aboveground S uptake varied significantly with the site. In 2019, Walcott had the highest total S uptake, significantly greater than the rest of the four sites; the lowest S uptake was observed at Downer, similar to Ada and Amenia (Figure 1). In 2020, Wheatland had significantly highest S uptake than Chaffee. Total S uptake ranged between 15.8 and 23.3 kg S ha^{-1}. An increase in total S uptake to S addition over control was observed at all sites except Wheatland in 2020.

4 | DISCUSSION

These outcomes from on-farm trials to determine corn response to S indicate that corn yield and S uptake were more responsive to growing season and site characteristics rather than fertilizer-S application rate. Previous research (Kaur et al., 2019) also found a lack of response to S and suggested that S from SOM and mineralization in some soils was enough for crop growth and hence, applied SO_4–S fertilizer had no effect on corn yield. Steinke et al. (2015) found that fine-textured soils in Michigan with relatively high SOM (>28 g kg^{-1}) and residual S > 6–8 mg kg^{-1} is enough to get maximum corn yield without application of S. Kim et al. (2013) found that yield response was not related to soil test SO_4–S and the probability and magnitude of the response decreased with increasing SOM concentration. They found that yield response was greatest when SOM concentration was <20 g kg^{-1}, less between 20 and 40 g kg^{-1}, and was not responsive when >40 g kg^{-1}. Kaiser and Kim (2013) observed that grain yield response to S in Minnesota was recorded only when SOM concentration was <20 g kg^{-1}. Franzen and Grant (2008) wrote that S deficiency in the northern Great Plains is highly affected by soil properties. In soils low in SOM, less S is released through mineralization, resulting in a greater likelihood of S deficiency.

In this study, SOM concentration ranged between 12 and 51 g kg^{-1}, but grain yield in none of these 12 sites showed a significant response to SO_4–S application. These findings suggest that neither SOM concentration nor SO_4–S soil test could predict corn response to S. Along with the SOM, the texture of soil may also affect the S availability. Many previous studies concluded that crops are grown on sandy soil show more response to the application of S than those with greater clay content. Rehm (2005) conducted a study in central, south-central, and southeastern Minnesota and observed that the application of S fertilizer increased corn grain yield on sandy soils. The optimum rate of S fertilizer ranged from 6.7 to 13.4 kg S ha$^{-1,}$ but the optimum rate of S fertilizer varied with site and year. They concluded that sandy soils with low SOM content (<20 g kg^{-1}) are more responsive to S fertilizer due to inadequate release of S from SOM via mineralization. Also, sulfates leach more readily in sandier soils, contributing to generally less available S after spring thaw and during the growing season after high rainfall events. But soils of north-central region contain gypsum deeper in the soil profile. Fargo (fine, smectitic, frigid Typic Epiaquert) and Bearden (fine-silty, mixed, superactive, frigid Aeric Calciaquoll) soil series contain traces to several percent gypsum below 30 cm of soil depth (USDA-NRCS Web Soil Survey, https://websoilsurvey.sc.egov.usda.gov/), which can meet the plant S demand. During the summer season, due to high evapotranspiration demand, dissolved gypsum (SO_4–S) from the subsurface of soil moves upward with soil water, and S becomes available for uptake by plants (Nachshon et al., 2013). In this study, none of these 12 sites showed a significant response to SO_4–S application having sandy loam, clay loam, and loamy sand textures. However, under normal moisture conditions, corn roots can reach the zone of gypsum accumulation by the V6–V8 growth stage and access plant available S below a 30-cm soil depth.

Crop residue S mineralization is an important process to fulfill plant S demands during the growing season (Kaur et al., 2018). Sulfur mineralization from previous crop residues may affect crop availability of S, but Kaur et al. (2018) also observed that S immobilization by soil can readily occur. This may be a major reason that corn does not respond to the application of S. More S mineralization was noticed for spring wheat residue with Fargo soil (Kaur et al., 2018). This may be due to the decomposition of crop residue at a rate greater than the mineralization of SOM. Hence, S mineralization is an important process that contributes S from mineralization during the crop cycle, but this is not generally considered during S analysis (Carciochi et al., 2019). This process should be considered as a way to adequately predict S availability for crops (O'Leary & Rehm, 1991), and it would improve the diagnosis of S deficiencies in crops (Carciochi et al., 2019).

Aula et al. (2019) found that S use efficiency of cereal crops around the world to be 18%. Low S use efficiency of cereals was mostly attributed to the leaching of SO_4–S from soil (Carciochi et al., 2019; Riley et al., 2002). In a sandy loam soil, (Riley et al., 2002) determined that 72% of fertilizers were leached, and none of the fertilizer S from the ammonium sulfate source remained in the experiment. Low adsorption of SO_4–S in soil with pH >6 and lack of immobilization of SO_4–S to organic S are the two main reasons behind low S retention capacity in temperate climate soils with a positive cation exchange capacity and very low anion exchange capacity.

Kurbondski et al. (2019) observed that S increased plant mass, plant S concentration, and S uptake at the V8 stage and leaf S concentration at the R2 stage but did not increase corn grain yield. They found that their increase in S concentration was due to applied S fertilizer available for uptake. Similar results were observed in this study. Corn S uptake significantly increased at the V6 stage with the application of S but did not affect corn grain yield and total S uptake at maturity.

5 | CONCLUSION

The S application did not increase corn yield. For most sites, S availability from mineralization might have been enough to optimize yield. Yield and S uptake varied across site and year. As a standard method of available soil, S does not give a reliable estimate of S availability. Growers should apply the current recommendation of 11–22 kg S ha^{-1} to reduce the chance of yield loss and compensate for the removal with grain. Further studies should focus on identifying site characteristics as well as deeper soil sampling (>30 cm) to help predict yield response besides SOM. Soil organic matter content is not a reliable predictor for corn response to S in the Red River Valley of North Dakota and Minnesota.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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