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CROP MANAGEMENT

Corn and soybean response to sulfur fertilizer in West Tennessee

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Abstract

With improved crop yields and reduced atmospheric S deposition, Mid-South U.S. soils may require S fertilization in deficient soils. The objectives of this study were to identify optimal at-planting S rate for corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] yield, and evaluate the impact of S rate on crop growth, leaf nutrient level, and seed S. Small plot replicated field studies were conducted in 2015 and 2016 at a S-deficient site in Milan, TN. Ammonium sulfate [$(NH_4)_2SO_4$] was broadcast applied at planting at 0, 10, 20, and 30 lb S acre^{-1}. Soybean leaf S concentration at early bloom was similar to the zero S control, but concentrations of Fe, Mn, and Cu were reduced, and Zn was increased. These effects increased with S rate. Corn leaf tissue S concentration increased with S rate at sixth-leaf and silking, while Fe, Mn, and Cu decreased as S rate increased, similar to the soybean experiment. Soybean seed S level increased with rate of S, while corn seed S increased with lowest S rate but did not respond to S rate. Seed N and seed weight were not affected by S rate for either crop. The small increase in soybean yield was not significant. Corn yield increased with applied S in both years. Overall, application of S fertilizer at ≥10 lb S acre^{-1} improved corn but not soybean yield in a low soil organic matter (SOM), S deficient medium-textured soil.

1 | INTRODUCTION

Sulfur is widely recognized as being an important nutrient for optimal plant growth and crop yield (Franzen & Grant, 2008). In the southeastern United States, soil S levels were generally adequate for crop yield except for coarse-textured soils low in organic matter (Kamprath & Jones, 1986). Sulfur deficiencies rarely occurred in Tennessee crops growing in medium- and fine-textured soils until the mid-2000s. More widely occurring S deficiency in the United States is attributed to an increased use of phosphate and other fertilizers with fewer S impurities (Chien et al., 2011; Hagstrom, 1986), reduced atmospheric S deposition that replenishes soil S (Scherer, 2001), and to higher crop yields where demand for S exceeds soil supply. Since 1970, the Clean Air Act has led to significantly reduced sulfur dioxide emissions, decreasing S deposition in many areas of the United States (U.S. Environmental Protection Agency, 2017). In West Tennessee, annual wet sulfate (SO_4^{2-}) deposition has decreased from 16 lb acre^{-1} in 1985, to ≤7 lb acre^{-1} in 2016 (National Atmospheric Deposition Program, 2016). Meanwhile, U.S. crop yields have increased steadily, with corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] mean national yields increasing by 3.6 and 1.4 tons acre^{-1}, respectively, from the 1970s decade compared to 2010 through 2019 (USDA-NASS, 2020).

Coarse-textured soils are typically well drained and lower in soil organic matter (SOM) (Franzen & Grant, 2008) and therefore are more likely to be S deficient (Savoy, 2005; Scherer, 2001), although more recent research reports S deficiency in medium- and fine-textured soils (Franzen, 2015; Kim et al., 2013; Sawyer et al., 2009). In moist, warm,

Abbreviations: SOM, soil organic matter.

well-aerated soils, organic S slowly mineralizes from SOM to form SO_4^{2-}–S which is available to plants (Schoenau & Malhi, 2008). Sulfur mineralization may increase in tilled soil, while conservation tillage may reduce early season S availability due to cooler soil temperatures (Hill, 2000). Crop uptake and leaching are typical means of S depletion in soil. Sulfate may leach through soil layers with precipitation and accumulate in subsoil layers (Friesen, 1991; Ritchey & de Sousa, 1997) potentially out of reach of crop roots.

Sulfur is crucial for many plant processes since it is a key component of certain amino acids and enzyme cofactors needed for growth as well as protein accumulation in seed (Sexton et al., 1998) although amount needed varies by crop. A summary by Hitsuda et al. (2008) suggests that soybean may require less S fertilizer for sufficiency than corn. Other research suggests corn might remove more S than soybean. Dick et al. (2008) reported crop S removal by corn and soybean were 16 and 12 lb acre^{-1} when grain yields totaled 207 and 51 bu acre^{-1}, respectively.

Sulfur rate can influence N uptake in corn (Caldwell et al., 1969). Steinke et al. (2015) reported corn yield increase from S occurred only at suboptimal N rates in fine-textured soils with >2.5% SOM. Similarly, Fox et al. (1964) and Chen et al. (2008) indicated that S rate improved N use efficiency of corn at lower N rates. Limited research suggests that S rate may affect uptake and tissue levels of some micronutrients in alfalfa (*Medicago sativa* L.) (Caldwell et al., 1969), chickpea (*Cicer arietinum* L.) (Islam, 2012), and tobacco (*Nicotiana tabacum* L.) (Sims et al., 1979) although this relationship has not been thoroughly examined in corn or soybean.

Corn yield increase from 10 lb S acre^{-1} are reported by Camberato et al. (2020) from side-dress S in Indiana, and by Kaur et al. (2019) in North Dakota in medium- to fine-textured soils. Sawyer et al. (2015) indicated corn benefited from an economic optimum S rate of 16 lb S acre^{-1} on fine-textured soils and 25 lb S acre^{-1} on coarse-textured soils in Iowa. Rehm (2005) reported increased corn yields from starter fertilizer containing S in a fine-textured soil low in organic matter in a conservation tillage field in Minnesota. There are fewer reports of soybean yield increase from S. While Gutierrez Boem et al. (2007) found positive yield benefits in Argentina, Kaiser and Kim (2013) reported soybean yield increases to S at only one location low in organic matter. Sulfur deficiency due to depleted soil level has been addressed more recently in Southeast U.S. university fertility publications in Tennessee (Savoy & Joines, 2016), Arkansas (Espinoza & Ross, 2008; Slaton et al., 2013), and Mississippi (Larson & Oldham, 2008; Oldham et al., 2008). Soil or tissue monitoring of S levels and applying fertilizer when visual symptoms of S deficiency occur in corn (Espinoza & Ross, 2008; Larson & Oldham, 2008) and soybean (Slaton et al., 2013) are indicated, although recommended S rate varies widely from 10 to 30 lb S acre^{-1} (Larson & Oldham, 2008; Savoy & Joines, 2016; Slaton et al., 2013).

Core Ideas

- Sulfur fertilizer increased grain yield in corn but not soybean.
- Corn leaf S and soybean seed S increased with S rate.
- Sulfur did not affect seed weight or seed N in corn or soybean.

Tennessee's adoption of conservation tillage (no-till) beginning in the 1970s has reduced soil erosion, but has not led to a substantial increase in SOM (Yin & Main, 2015), an important source of S. The University of Tennessee currently recommends application of 10 lb S acre^{-1} to corn or soybean growing in a coarse-textured soil where symptoms of S deficiency have occurred in past crops (Savoy & Joines, 2016). However, producers commonly apply higher S rates to corn and soybean on medium- and fine-textured soils. At Milan, TN, a S rate study was conducted on a medium-textured soil with known S deficiency. The objectives of this experiment were to identify optimal S rate for yield in corn and soybean, and the impact of S rate on crop growth, leaf S, and micronutrient concentration, and seed S in a conservation tillage system. Results of the yield experiment will be used to confirm S fertility recommendations for these crops in Tennessee.

TABLE A Useful conversions

To convert Column 1 to Column 2, multiply by	Column 1 suggested unit	Column 2 SI unit
2.54	inch, in	centimeter, cm (10^{-2} m)
0.405	acre, ac	hectare, ha
5/9(°F–32)	Fahrenheit, °F	Celsius, °C
0.454	pound, lb	kilogram, kg
62.71	56-lb bushel per acre, bu/acre	kilogram per hectare, kg/ha
67.19	60-lb bushel per acre, bu/acre	kilogram per hectare, kg/ha

2 | EXPERIMENTAL PROCEDURES

2.1 | Site description

No-tillage S rate experiments were conducted in 2015 and 2016 without irrigation at the Milan Research and Education Center in Milan, TN (35.9198° N, 88.7589° W). The primary soil type was a Collins silt loam (coarse-silty, silty, mixed, active, acid, thermic Aquic Udifluvent). Soil samples (0–6 inches) were collected from each plot before fertilizer application on 21 Mar. 2015 and 12 Apr. 2016, air dried, ground, and analyzed by Waypoint Analytical (Memphis, TN) using Mehlich-3 extraction (Mehlich, 1984). Across 2 yr for the test site, soil pH was 6.7 and SOM averaged 1.8%, P of 66 ppm, K of 154 ppm, SO_4^{2-}–S of 6.7 ppm, Mg of 43 ppm, Zn of 1.1 ppm, B of 0.4 ppm, and Mn of 171 ppm. Following 2015 harvest, soil samples were collected from each corn and soybean plot at 0-to-24-inch depth in 8-inch increments, and treatments combined across replicates to determine post-harvest S levels at different depths. Sulfate-S was measured using the method previously described. In both years, P and K fertilizers were applied according to University of Tennessee recommendations as triple superphosphate [(Ca $H_2PO_4)_2.H_2O$] and muriate of potash (KCl), respectively. Experiments were weed free and insects and diseases were managed as needed by following University of Tennessee recommendations (Steckel et al., 2016; Stewart & McClure, 2016). Precipitation and temperature data were recorded throughout each growing season with a NOAA weather station located near the trial site, and data were obtained from (https://www.ncdc.noaa.gov/cdo-web/datasets/GHCND/stations/GHCND:USC00406012/detail).

2.2 | Experimental methods

All experiments employed a randomized complete block design with four S application rates (0, 10, 20, and 30 lb S acre^{-1}) and six replications. Plots were four rows and 10 ft wide by 30 ft long, with an inter-row spacing of 30 inches. The previous crop before soybean each year was corn, and the previous crop before corn each year was soybean. Each experiment used the same plot randomization for S rate in both locations in 2015 and 2016, which allowed a S rate to be applied to the same plot within experiments each year, and corn and soybean crops to be rotated between sites in 2016. Asgrow 4632 (Monsanto Company, St. Louis, MO) was the soybean variety, planted into no-tillage on 7 May 2015 and 24 May 2016 at a depth of 1 inch and at a seeding rate of 145,000 seeds acre^{-1} in both years. In 2015, the corn hybrid was Dekalb 66-97 (Monsanto Company, St. Louis, MO) and Dekalb 66-87 (Monsanto Company, St. Louis, MO) was the hybrid in 2016 because Dekalb 66-97 was not available. Corn was planted on 28 Apr. 2015 and 8 Apr. 2016 at a depth of 2 inches and at a seeding rate of 34,000 seeds acre^{-1} both years.

Sulfur was broadcast evenly by hand to plots as granular ammonium sulfate [$(NH_4)_2SO_4$] before planting corn (28 Apr. 2015 and 8 Apr. 2016) or soybean (8 May 2015 and 24 May 2016). Ammonium sulfate contains N, therefore, to ensure that all plots received the same amount of N at planting, ammonium nitrate (NH_4NO_3) was applied to the zero S control, blended with $(NH_4)_2SO_4$ at an appropriate amount with 10 and 20 lb acre^{-1} rates, and excluded from the highest S rate treatment, since it was used as the benchmark for determining the amount of N to be added to other plots. Each soybean plot received a total of 40 lb N acre^{-1} as $(NH_4)_2SO_4$, NH_4NO_3, or a combination of both depending on treatment. Each corn plot received a total of 180 lb N acre^{-1} that included 40 lb N acre^{-1} from at-planting $(NH_4)_2SO_4$, NH_4NO_3, or a combination of both depending on treatment. The remaining 140 lb N acre^{-1} was applied to corn in a side-dress of liquid urea ammonium nitrate (UAN) injected behind a coulter in each inter-row middle of each plot. About 15 random leaves were taken from each plot when at least 50% of plants had reached early soybean bloom or silking (R1) (Licht, 2014) in 2015, and sixth-leaf (V6) and R1 (Abendroth et al., 2011) stage corn in 2015 and 2016. Following SAAESD recommended procedures (SAAESD, 2000), the youngest fully developed trifoliate was chosen in soybean, the uppermost leaf with a visible collar was chosen at V6 corn, and the leaf directly below the corn ear at R1. Tissue samples were dried at 60 °C, ground, and analyzed by a commercial lab (Brookside Laboratories, Inc., New Bremen, OH) using nitric acid and hydrogen peroxide digestion in a CEM Mars Express microwave system. The digested sample was then analyzed on a Thermo 6500 Dou ICP, for N, P, K, S, Mg, and micronutrients. Soybean height was measured from the ground to the youngest developed soybean trifoliate when bean plants were at seed-fill stage (R5). Corn height was measured at two separate times, once from the ground to the youngest developed leaf at the fifth-leaf stage (V5) and once after silking (R1) from the ground to the tip of the tassel, using a fiberglass telescoping measuring rod.

The center two rows of each plot were harvested with a research grade plot combine (Kincaid Equipment Mfg., Haven, KS) equipped with a weigh system to determine soybean and corn seed yield, moisture, and test weight. Yield data were reported at 13% moisture for soybean and 15.5% moisture for corn. At harvest, a grain subsample was collected from each plot and 100 seeds were weighed to estimate seed weight. Grain subsamples for soybean (2015 and 2016) and corn (2015) were then analyzed (Brookside Laboratories) for seed S and N, being digested with nitric acid and hydrogen peroxide in a CEM MARS Express microwave system. The digested sample was then analyzed on a Thermo 6500 Dou ICP.

2.3 | Statistical analysis

Data were subjected to a mixed model ANOVA using PROC GLIMMIX procedure in SAS 9.4 (SAS Institute, 2011). Fixed effects included S treatment, year, and the S treatment × year interaction, while replication was random. For variables that were only measured in a single year, the analysis did not include year effects. Least square means were compared using Fisher's least significant difference (LSD) at the 95% confidence level ($P < .05$). Data were analyzed across years where appropriate for mean separation and contrasts among treatments. PROC GLM (SAS Institute, 2011) was used to examine the relationship of actual soybean and corn yield and corn height with S rate. Figures were generated in Microsoft PowerPoint (ver. 2016).

3 | DISCUSSION

3.1 | Environmental conditions

Growing conditions were mostly favorable for both crops in 2015, with optimal spring planting conditions, wetter conditions in May, adequate seasonal rainfall, and temperatures close to normal (Table 1). Early season dry weather in 2016 allowed timely spring planting but dryer than normal conditions in May and June combined with slightly warmer mid-season temperatures resulting in a more yield-limiting environment for corn in 2016 compared to 2015. Excellent rainfall in August 2016 favored soybean, creating a higher yield environment in 2016 than 2015.

3.2 | Soil S measurements

The site chosen for this experiment was selected because it had a history of visual S deficiency in corn. The University of Tennessee does not currently have a calibration for any soil available S analytical method, therefore, a commercial lab (Waypoint Analytical) routinely used by producers in Tennessee, analyzed soil S during this experiment. Pre-plant (2015 and 2016) and post-harvest (2015) soil S data were combined across replications and an average is reported by S rate in Table 2. In 2015, at the initiation of the study, pre-plant soil S at 0–6 inches was similar across all planned S rates for both corn and soybean. Soil S (0–6 inches) prior to planting was higher in 2016 for both crops, but ≤10.3 ppm regardless of S rate applied the previous year (Table 2). The commercial lab that performed the soil analyses recommends S application when soil SO_4^{2-}–S levels fall below 22 ppm, indicating the experimental area was S deficient, confirmed

TABLE 1 Monthly total precipitation and average temperature and departure from the 30-yr normal (DN) in Milan, TN, 2015 and 2016. Data were collected from the Milan, TN, reporting weather station located near field site

Month	Precipitation				Temperature			
	2015		2016		2015		2016	
	Total	DN	Total	DN	Total	DN	Total	DN
	inches				°F			
Apr.	4.4	−0.6	2.8	−2.2	61.3	1.2	60.4	0.7
May	10.3	4.4	4.3	−1.7	68.9	0.3	66.6	−1.0
June	6.0	1.6	1.7	−2.8	78.1	1.2	79.2	1.8
July	3.3	−1.1	3.4	0.1	81.3	1.3	82.4	1.9
Aug.	4.7	1.4	6.1	2.1	75.7	−1.4	80.4	1.2
Sept.	2.5	−1.4	1.0	−2.9	72.5	0.8	75.0	2.2
Oct.	3.4	0.1	0.6	−3.0	60.6	0.8	66.2	−2.7

TABLE 2 Pre-plant soil S concentration (0–6 inches) and 2015 post-harvest soil S concentration (0–24 in) in corn and soybean experiments at Milan, TN

Treatment[a]	Corn		Soybean		Post-harvest					
	2015	2016	2015	2016	2015 following corn[c]			2015 following soybean[c]		
	Pre-plant[b]				0–8 inches	8–16 inches	16–24 inches	0–8 inches	8–16 inches	16–24 inches
	0–6 inches									
lb S acre^{-1}	ppm									
0	3.9	10.0	4.5	8.5	6.8	5.9 c	5.2 b	6.3 b	5.7 c	5.2 b
10	2.7	9.0	4.8	10.3	7.2	6.2 bc	6.5 ab	7.0 ab	6.8 ab	6.8 a
20	3.2	9.3	4.8	8.7	7.3	7.0 ab	9.2 a	7.2 a	6.3 bc	7.3 a
30	4.0	10.0	4.2	9.0	7.3	7.5 a	9.0 a	7.5 a	7.3 a	7.7 a
P > *F*	ns	ns	ns	ns	ns	.01	.03	.04	<.01	.01

Note: ns, not significantly different at the .05 probability level.

[a]Treatment consisted of ammonium sulfate [$(NH_4)_2SO_4$] applied at planting at rates of 0, 10, 20, and 30 lb S acre^{-1}.

[b]Average across replicates from four to five soil cores taken from the center of each plot at 0-to-6-inch sampling depth.

[c]Average across replicates from four to five soil cores taken from the center of each plot at 0-to-8-, 8-to-16-, 16-to-24-inch sampling depth.

[d]Means in the same column followed by the same letters are not significantly different at the .05 probability level.

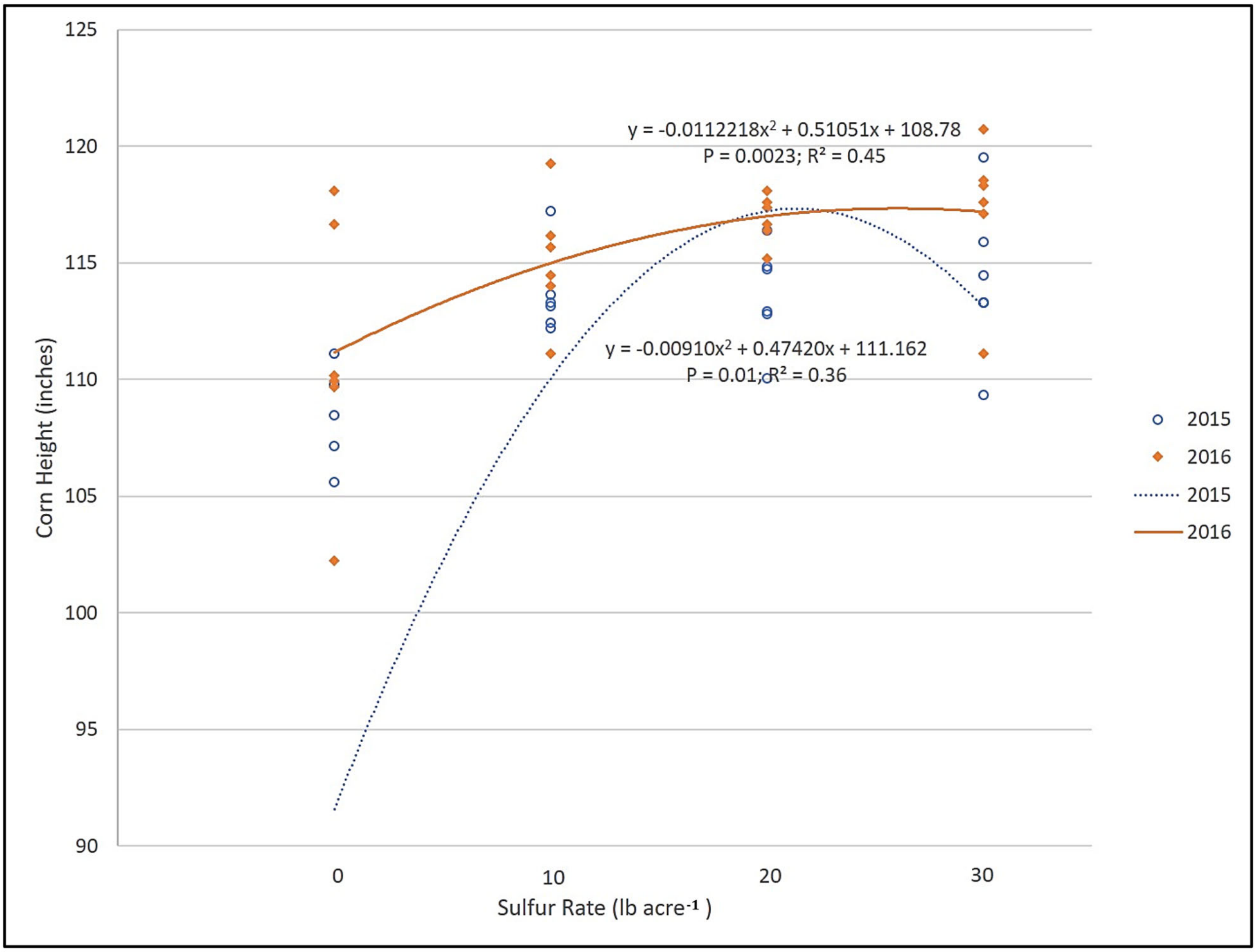

FIGURE 1 Relationship of actual corn height at silking (R1) to S rate at Milan, TN, in 2015 and 2016

TABLE 3 Leaf S concentration in soybean (2015) and corn (2015 and 2016) at Milan, TN

Treatment[a]	Soybean stage[b]	S Tissue concentration percentage	Corn stage[b]	S Tissue concentration percentage	
		2015		2015	2016
lb S acre^{-1}	R1	%	V6	—%—	
0		0.28[c]		0.25 c	0.28 c
10		0.28		0.31 b	0.43 b
20		0.28		0.34 ab	0.47 a
30		0.29		0.37 a	0.48 a
P > *F*		ns		.001	.003
Treatment					
lb S acre^{-1}			R1	2015 & 2016	
0				0.17 b	
10				0.21 a	
20				0.21 a	
30				0.22 a	
P > *F*				<.0001	

Note: ns, not significantly different at the .05 probability level.

[a]Treatment consisted of annual at-planting ammonium sulfate [$(NH_4)_2SO_4$] at rates of 0, 10, 20, and 30 lb S acre^{-1}.

[b]Crop leaves used for leaf tissue analysis were youngest fully developed leaf for soybean (R1) and corn (V6) and ear leaf for corn (R1).

[c]Means in the same column followed by the same letters are not significantly different at the .05 probability level.

TABLE 4 Nutrient concentrations of early bloom (R1) soybean leaves sampled in 2015 at Milan, TN

Treatment[a]	Soybean R1[b] tissue analysis					
	Mg	B	Fe	Mn	Cu	Zn
lb S acre^{-1}	%	—ppm—				
0	0.39 a[c]	31.3 a[c]	101.1 a	96.9 a	8.7 a	28.2 b
10	0.35 b	28.1 b	88.3 b	95.9 a	8.5 a	37.5 a
20	0.37 ab	25.7 c	79.1 c	91.8 ab	8.4 ab	35.4 a
30	0.36 b	25.2 c	73.6 c	85.3 b	7.6 b	34.4 a
P > *F*	.01	<.0001	<.0001	.01	.04	.001

[a]Treatment consisted of ammonium sulfate [$(NH_4)_2SO_4$] applied annually at-planting at rates of 0, 10, 20, and 30 lb S acre^{-1}.

[b]Youngest fully developed trifoliate soybean leaves were sampled at R1 growth stage.

[c]Means in the same column followed by the same letters are not significantly different at the .05 probability level.

TABLE 5 Nutrient concentrations of corn leaves sampled at sixth leaf (V6) and silking (R1) across 2015 and 2016 at Milan, TN

Treatment[a]	V6 Tissue analysis[b]			R1 Tissue analysis[b]	
	Fe	Mn	Cu	Mn	Cu
lb S acre^{-1}	—ppm—				
0	447.8 a[c]	152.7 ab	18.9 a	145.6 a	13.9 a
10	435.9 a	159.8 a	18.7 a	125.9 bc	12.8 a
20	444.5 a	159.6 a	18.2 a	130.2 b	12.5 ba
30	321.0 b	130.4 b	15.3 b	112.9 c	11.3 b
P > *F*	.02	.04	.006	.001	.01

[a]Treatment consisted of annual application at-planting of ammonium sulfate [$(NH_4)_2SO_4$] at rates of 0, 10, 20, and 30 lb S acre^{-1}.

[b]Corn leaves were sampled at V6 and ear leaf (R1) growth stage and nutrients were measured in parts per million.

[C]Means in the same column followed by the same letters are not significantly different at the .05 probability level.

TABLE 6 Harvested seed S and seed N concentration over 2015 and 2016 for soybean and 2015 for corn at Milan, TN

Treatment[a]	Soybean 2015 and 2016		Corn 2015	
	Seed S	Seed N	Seed S	Seed N
lb S acre^{-1}	%			
0	0.23 c[b]	5.8	0.9 b	1.2
10	0.27 b	5.9	1.1 a	1.3
20	0.29 a	5.8	1.1 a	1.3
30	0.29 a	5.8	1.1 a	1.4
$P > F$	<.0001	ns	.001	ns

Note: ns, not significantly different at the .05 probability level.
[a]Treatment consisted of annual application of at-planting ammonium sulfate [$(NH_4)_2SO_4$] at rates of 0, 10, 20, and 30 lb S acre^{-1}.
[b]Means in the same column followed by the same letters are not significantly different at the .05 probability level.

TABLE 7 Grain yield of soybean and corn at Milan, TN, in 2015 and 2016

Year	Treatment[a]	Soybean yield	Corn yield
	lb S acre^{-1}	bu acre^{-1}	
2015	0	51	203 b[b]
	10	54	217 a
	20	53	228 a
	30	53	221 a
	$P > F$	ns	.004
2016	0	62	80 b
	10	63	111 a
	20	64	116 a
	30	62	123 a
	$P > F$	ns	.0008

Note: ns, not significantly different at the .05 probability level.
[a]Treatment consisted of annual at-planting ammonium sulfate [$(NH_4)_2SO_4$] at rates of 0, 10, 20, and 30 lb S acre^{-1}.
[b]Means in the same column followed by the same letters are not significantly different at $P \leq .05$.

by soil testing. Deeper soil sampling following the 1st year of S fertilization appears to show extractable sulfate S levels were increased significantly above the zero S check at deeper depths, particularly with higher S rates, indicating some movement through the soil profile. However, all concentrations were <10 ppm regardless of S rate or depth (Table 2).

3.3 | Impact of S on crop growth and leaf nutrient concentration

Soybean height at R5 did not vary with S rate in either year (data not shown), while all rates of S increased corn height compared with the zero added S control (Figure 1). A significant year effect ($P \leq .04$) for corn height was likely from planting a different cultivar the 2nd year, since corn was taller in 2016 (a dryer year). Corn height increased with 10 lb S acre^{-1} but did not increase significantly more at higher S rates. There was a quadratic effect of S rate on height ($P \leq .0023$ and $P \leq .01$) for 2015 and 2016, respectively (Figure 1).

Crop leaves were sampled at developmental stages recommended by the SAAESD (Southern Cooperative Series Bulletin: Reference Sufficiency Ranges for Plant Analysis in the Southern Region of the United States, 2000) and results compared to the standard critical values for nutrient sufficiency (SAAESD, 2000). There were no visual differences in soybean canopy color at R1 in either year or late season in 2016. Soybean leaf S concentrations of 0.28–0.29% (Table 3) did not differ with treatment ($P > .12$), indicating no S rate response at early bloom in 2015. Values were within the sufficiency range of 0.25–0.6%, indicating early bloom concentrations for all treatments were sufficient. Later that year, canopy color differences were observed in the crop at seed-fill stage (R5) that appeared to be treatment related. The normalized difference vegetation index (NDVI) measurement indicated significant differences ($P \leq .02$) in canopy greenness compared to

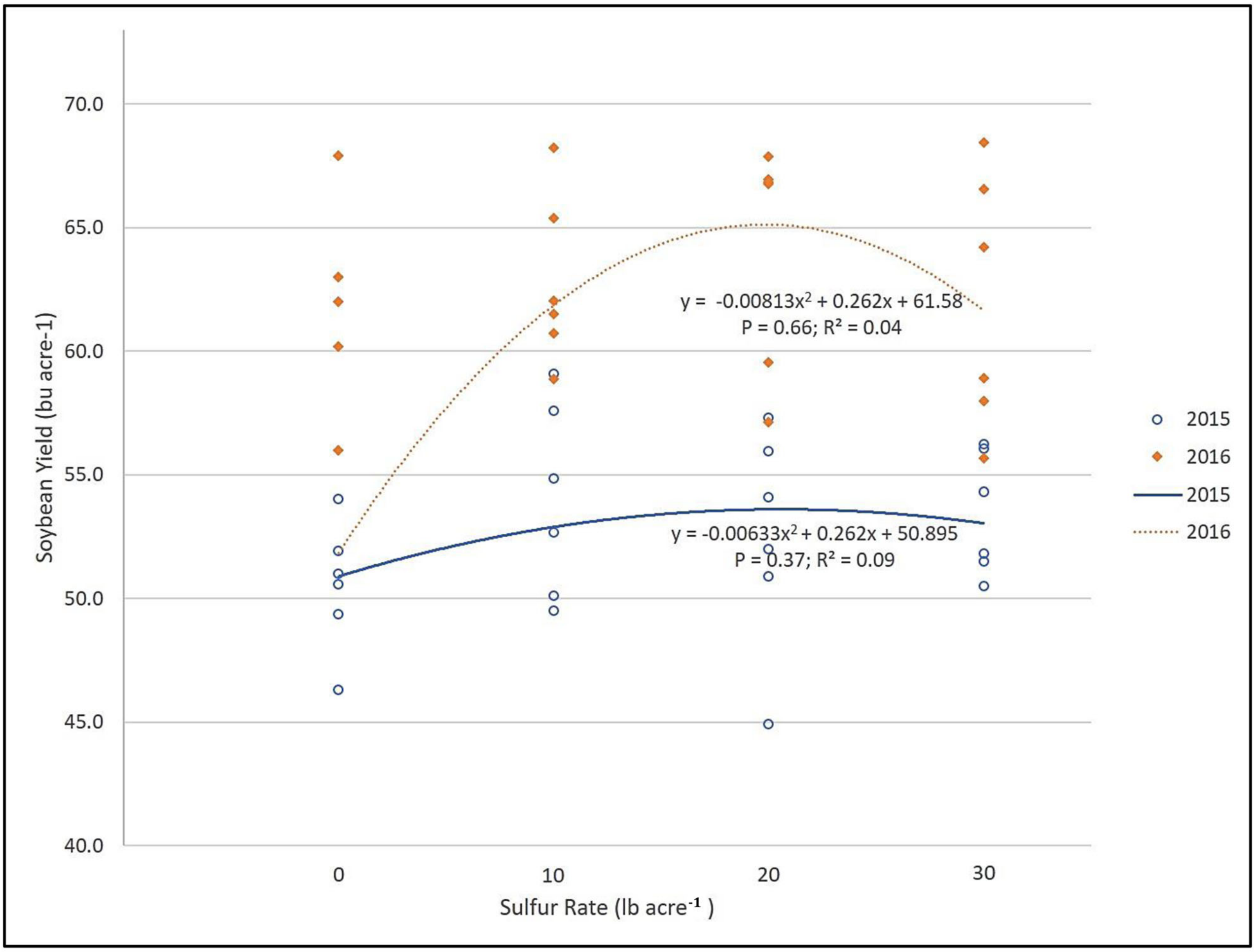

FIGURE 2 Soybean yield response to S rate at Milan, TN, in 2015 and 2016

the zero S check, suggesting S uptake had some influence on canopy greenness late in the 2015 season (data not shown). Hitsuda et al. (2008) suggested that tissue S concentration measured at early flowering stage may be a poor indicator of crop deficiency in soybean; however, Kaiser and Kim (2013) correlated V5 whole plant S and trifoliate S level at full flowering (R2) to soybean yield response, which suggests an early season S measurement may still be important for explaining yield results.

Sulfur concentration in corn leaves increased with S rate at both sampling times (Table 3), with a significant ($P \leq .04$) year × S rate interaction effect on V6 concentration but not R1. Higher leaf S concentrations at V6 followed 20–30 lb S acre^{-1}, however, this trend did not continue at R1. Kim et al. (2013) suggested that corn may take up S in greater amounts than actually needed for grain yield. O'Leary and Rehm (1990) observed ear leaf S increased with increasing rate of S at 6 of 10 sites on three different silt loam and one sandy loam soil from S applied at 10, 20, and 50 lb S acre^{-1}. Tissue concentrations were greater in 2016 than in 2015, possibly due to hybrid uptake differences as reported in some research (Bender et al., 2012) or from accelerated uptake following a rain event prior to sampling. Sulfur concentration in leaves at R1 also increased with all S rates, with no significant increase at rates above 10 lb S acre^{-1}. Corn plots were visually greener where S was applied in both years, with two different cultivars, but this was not supported by S tissue results. Leaf tissue S levels at V6 and R1 met or exceeded the sufficiency range of 0.15–0.40% and 0.16–0.6%, respectively (Southern Cooperative Series Bulletin: Reference Sufficiency Ranges for Plant Analysis in the Southern Region of the United States, 2000) for the zero S control as well as where S was applied (Table 3). These results are similar to Steinke et al. (2015) who reported sufficient leaf tissue S in corn leaves even under conditions when S application increased crop yield. This indicates the current sufficiency leaf S range for corn may be too low, and is not always an indicator of crop nutrient status.

Leaf concentration of other nutrients varied with S rate, with differences between the two crops. In 2015, R1 soybean leaf concentrations of Mg, B, and Fe were consistently lower than the zero S control at all S rates, while Zn level increased at all S rates (Table 4). Manganese and Cu concentrations

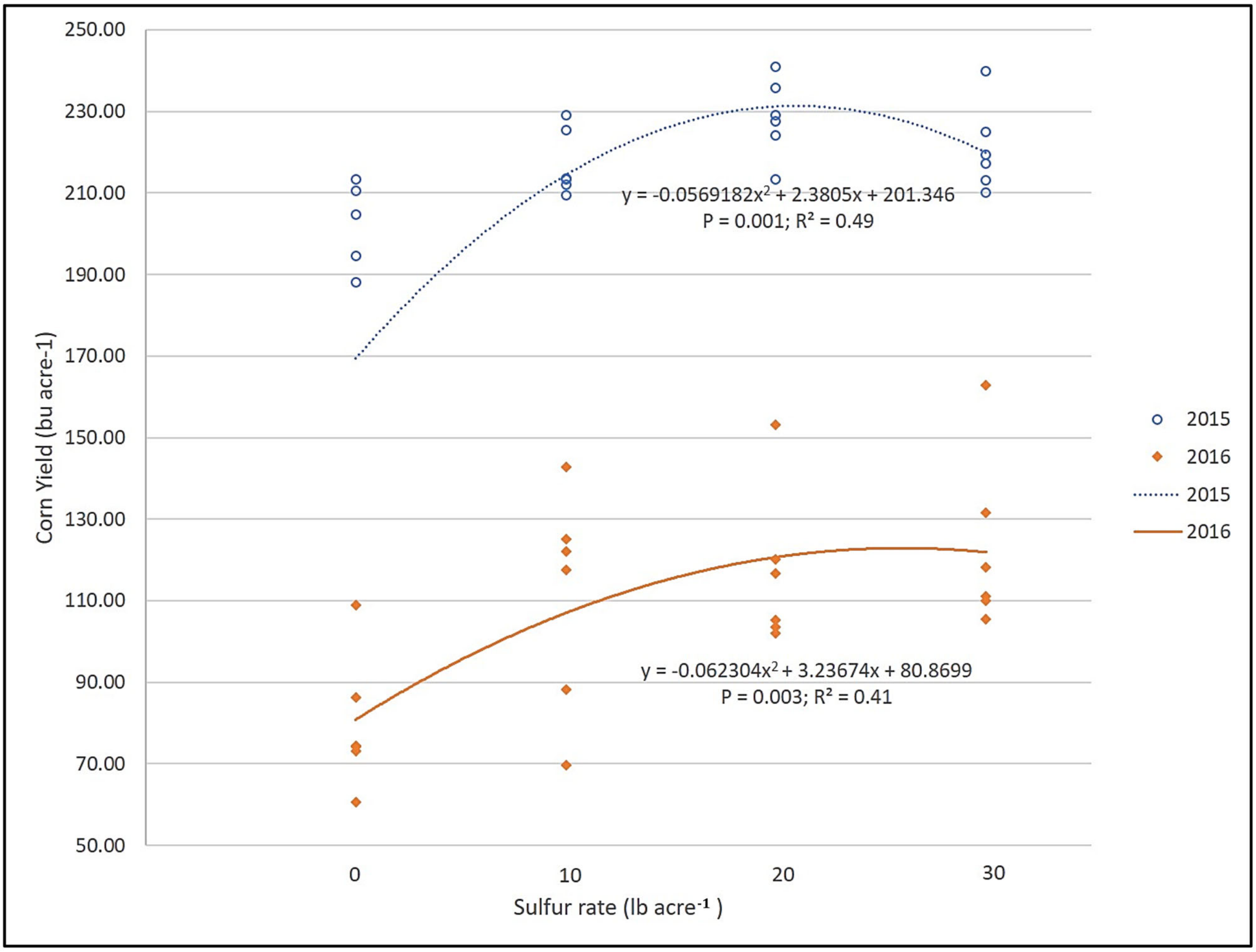

FIGURE 3 Corn yield response to S rate at Milan, TN, in 2015 and 2016

were reduced only at the highest S rate of 30 lb acre^{-1}. Islam (2012) reported increased Zn uptake in chickpea with $(NH_4)_2SO_4$ at 13–27 lb S acre^{-1}, attributed to enhanced availability with pH reduction as a result of S fertilizer application. Soybean leaf concentrations of P, K, Al, or Na were not affected by S rate (data not shown). At V6, corn leaf Fe, Mn, and Cu concentration was reduced following 30 lb S acre^{-1}, but was not significantly impacted at lower S rates (Table 5). Ear leaf tissue Mn levels decreased with all S rates, while Cu levels declined only at 30 lb S acre^{-1} (Table 5). Our results differ from Rahman et al. (2011) who measured increased Mn uptake in corn from elemental S application attributed to temporary soil acidification by S fertilizer. Ear leaf concentrations of Fe, Al, and Zn differed with year with no clear response to S (data not shown). Sulfur fertilization did not alter corn leaf levels of N, P, K, Mg, B, or Zn at either sampling timing (data not shown). Caldwell et al. (1969) reported that 50 lb S acre^{-1} as gypsum decreased Cu tissue concentration in corn, but also decreased B and P in corn, which differed from our results.

3.4 | Impact of S on seed measurements

For both crops, seed weight differed by year (data not shown) and did not respond to S application ($P \leq .08$ and $P \leq .4$) for soybean or corn, respectively, at the .05 probability level. Seed S percentage increased in both soybean (2015, 2016) and corn (2015) with as little as 10 lb acre^{-1} added S (Table 6). Soybean seed S increased with increasing S rate, while corn seed S percentage did not change from 10 to 30 lb S acre^{-1} rates (Table 6). There appeared to be no S fertilization effect on seed N percentage for corn. Soybean seed N percentage did not change with S, which is similar to findings in non-irrigated soybean by Bellaloui et al. (2011), possibly because of lower uptake and N mobility under non-irrigated conditions. Gaspar et al. (2018) identified greater S removal in soybean seed after mid-seed fill and as yield levels improved. Multiple researchers indicate both soybean (Kaiser & Kim, 2013) and corn (Kim et al., 2013) may take up S in higher quantities than needed to support growth, since increased seed uptake was not always related to yield.

3.5 | Corn and soybean yield response to S rate

There was expectation of increased soybean yield at this site, due to low soil S, SOM of <2%, and because the previous year's (2014) corn crop had exhibited S deficiency symptoms. Soybean yielded higher in 2016 than 2015, creating a significant year effect ($P < .0001$), but not a significant S rate effect on yield (Table 7). In 2016, plots received timely later season rainfall during critical reproductive stages, which improved yield. Neither linear (not shown) nor quadratic regression models described the relationship between soybean yield and S rate (Figure 2). Soybean yields trended higher following S, but differences were not significant. Yield response to S in non-irrigated soybean has been inconsistent (Bellaloui et al., 2011; Lawson, 2012; Sawyer & Barker, 2002), although other researchers have successfully correlated soybean yield to seed S removal (Gaspar et al., 2018; Kaiser & Kim, 2013), or leaf or whole plant S concentration (Kaiser & Kim, 2013). Growers often apply S based on soil testing results. Although this trial site had low extractable S levels, they did not correspond to increased soybean yield with S fertilization, a finding similar to Kaiser and Kim (2013). Since our yields were average but not exceptional for Tennessee growing conditions, lack of yield response to S in our experiment may have been due to other yield-limiting factors, such as soil yield potential.

In our medium-textured soil, corn grain yield increased above the zero S control by 7–9% with Dekalb 66-97 in an adequate rainfall year (2015) and by 39–54% with Dekalb 66-87 in a year with in-season drought (2016). In each year, yield with S at 10 lb acre^{-1} was similar to other S rates (Table 7).Year effect was significant ($P \leq .0001$) probably because of lower yield environment in 2016 although S uptake may vary by cultivar (Bender et al., 2012). Corn yield increase with S rate could be described with a quadratic model for both 2015 ($P \leq .001$) and 2016 ($P \leq .003$) (Figure 3). Maximum yield increase in a good rainfall year (2015) was with 20 lb S acre^{-1} while 25 lb S acre^{-1} gave maximum yield response in a dry year (2016). Other recent investigations in medium-textured soils have demonstrated corn yield increase in some locations with at-planting S (Kaur et al., 2019; O'Leary & Rehm, 1990; Rehm, 2005; Sawyer et al., 2009) with lack of response in all sites attributed to adequate soil organic matter for S mineralization. In Iowa, Sawyer et al. (2015) reported an economic optimum S rate was 16 lb acre^{-1} on fine-textured soils and 25 lb acre^{-1} on coarse-textured soils. Corn tissue uptake increased with all S rates while yield did not respond similarly, supporting the theory that the corn plant may take up more S than is needed for final grain yield (Kim et al., 2013).

4 | CONCLUSIONS

While our results support amending the current University of Tennessee recommendation for S in corn to include S application at ≥10 lb S acre^{-1} to low SOM medium-textured soils with a history of S deficiency, additional site-years will be required to more fully support that conclusion. Our current findings do not support an S application to soybean on a medium-textured soil. However, although S application did not increase yield in soybean, there were measurable increases in seed S which may have seed quality implications for soybean produced for livestock feed.

In these trials, plant tissue analysis did not indicate deficiency for either crop, even where visual symptoms were observed between treatments (corn early season both years and NDVI differences were detected late-season soybean in 2015) and spring soil S levels would have triggered an application by a commercial lab. This indicates the current sufficiency levels for corn may be too low, and tissue testing in corn may not be a reliable way to determine need for early-season S, even in environments where treatment might be beneficial. In soybean, early tissue sampling at R1 was probably too early and not useful for predicting later season S sufficiency.

AUTHOR CONTRIBUTIONS

K. Cannon: Formal analysis, Investigation, Writing-original draft, Writing-review & editing, M. A. McClure: Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Writing-review & editing, X. Yin: Conceptualization, Writing-review & editing, C. Sams: Conceptualization, Writing-review & editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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