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Soybean Yield Response to Sulfur and Nitrogen Additions Across Diverse US Environments

Sulfur Fertility Overview

Sulfur (S) fertility recommendations in soybean have become more frequent due to the use of fertilizers with little to no S, less S atmospheric deposition, and higher crop yields (Dick et al., 2008; Kanwar & Mudahar, 1983). As soybean yields reach record highs, more nutrients are required to maintain these production levels. Producers are interested in fine tuning their fertility programs to supply adequate nutrients for both plant and soil health, while also maximizing profits. Only a small percentage (5-10%) of S in the soil is plant-available, the rest is stored as organic matter and slowly broken down into plant-available form over time (Schoenau & Germida, 1992; Schoenau & Malhi, 2008).

Past Sulfur Fertility Trials in Soybean

Most research has concluded that S is not currently limiting in US soybean production systems (Borja Reis et al., 2021; Cannon et al., 2021; Letham et al., 2021; Moro Rosso et al., 2020; Roysdon, 2021). Additionally, previous studies state that soil-test S is not a good indicator of S deficiency (Letham et al., 2021). Plant tissue or grain analysis are better detectors of S deficiency (Divito et al., 2015; Hitsuda et al., 2008). This makes S recommendations difficult, as optimal S application time may have passed before a deficiency is observed.

Soybean response to N additions is highly dependent on the environment and can marginally improve yield (Mourtzinis et al., 2018). Nitrogen additions may improve yield, especially in high-yield environments, but they usually are not profitable in soybean production (Beard & Hoover, 1971; La Menza et al., 2017, 2019; Salvagiotti et al., 2008). Although N additions are not typically recommended for soybean, one of the major sources of S, ammonium sulfate (AMS), contains N; therefore, this study examined N and S fertility interactions.

Trial Objectives

In this study, we aim to evaluate the effect of S and N applications on soybean yield and profitability in diverse environments across the US.

Tested Products and Rates

Tested sulfur-containing fertilizers include ammonium sulfate (AMS; 21-0-0-24) and calcium sulfate ($CaSO_4$; 0-0-0-17). To better understand the N impact in the AMS treatment, a urea (46-0-0) treatment was also included. All locations included a no-fertilizer control. Full information on fertilizer rates are available in Table 1. Tested rates of sulfur were 0 – 30 lbs, which represents the average total S uptake for soybeans (14-17 lbs/A) (Gaspar et al., 2018; Salvagiotti et al., 2021).

Image 1. Soybeans growing in Eastern Virginia, a site which did not show a significant response to S fertilization.

Abbreviations:

AMS
ammonium sulfate

$CaSO_4$
calcium sulfate

HSD
honest significant difference

Take Home Points

- Sulfur additions are less likely to impact soybean yield in lower yielding environments.
- Nitrogen additions marginally increased yields but did not increase profits.
- Most sulfur and nitrogen additions did not increase profits.

Table 1. List of treatments with amounts of nutrients supplied and estimated cost.

TREATMENT	†COST	FORM	RATE	S SUPPLIED	N SUPPLIED
	$/A			LB/A	
1		CONTROL		0	0
2	7.26	AMS‡	Low	10	9
3	14.53	AMS	Med.	20	18
4	21.79	AMS	High	30	27
5	5.38	$CaSO_4$	Low	10	0
6	10.75	$CaSO_4$	Med.	20	0
7	16.13	$CaSO_4$	High	30	0
8	3.79	Urea	Low	0	9
9	7.79	Urea	Med.	0	18
10	11.19	Urea	High	0	27

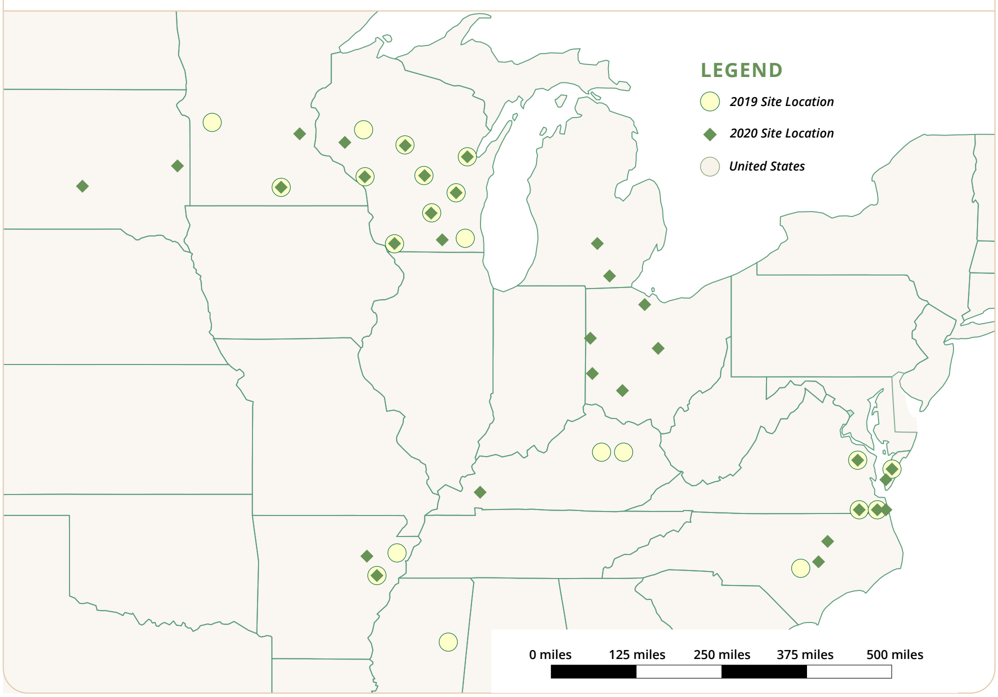
† Cost of treatment based on price estimates from 2019-2020 fertilizer without application costs in study area. Price estimates are as follows: $0.17/lb AMS, $0.09/lb $CaSO_4$, $0.20/lb Urea, and an application cost of $5.09/A.

‡ Ammonium sulfate

Trial Methods

Small-plot field trials took place at 52 sites in ten states in 2019 and 2020 (Figure 1). Ten treatments (Table 1) were replicated four to six times at each site in a randomized complete block design. Yield data were collected using plot combines and adjusted to 13% moisture content. Fertilizer and application cost estimates were determined by averaging estimates given by retailers and researchers in the study region in 2019 and 2020 (Table 1). Application costs were estimated at $5.09/A and were added to each treatment cost since many soybean programs do not include dry fertilizer application. Partial profits were calculated at two soybean prices ($14.98 and $8.72/bu) to be representative of current prices as well as the average price during the study (USDA-NASS, 2021). Details on the statistical analysis used can be found in the scientific publication at https://doi.org/10.1002/agj2.21216.

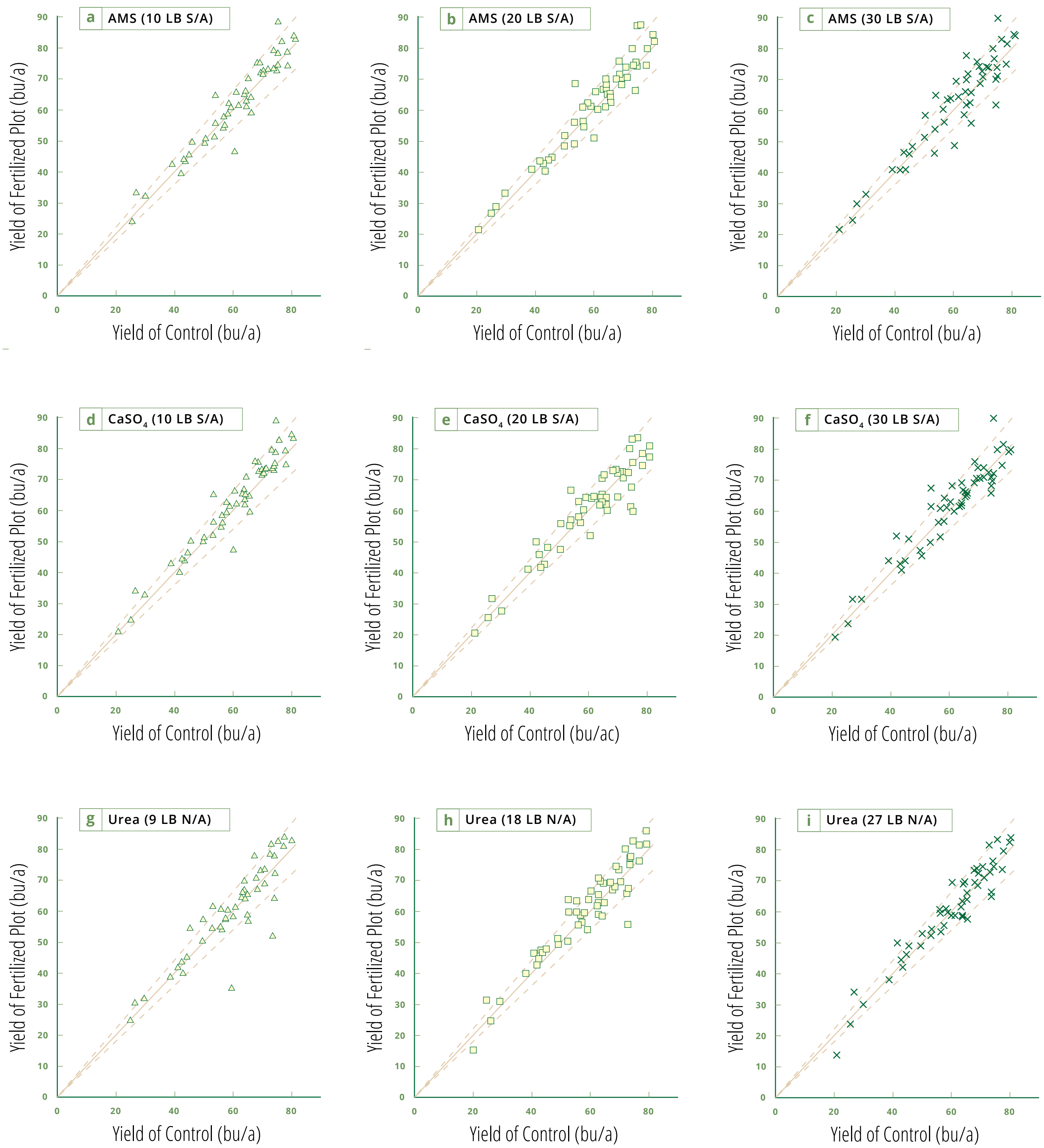
Figure 1. Trial sites in 2019 and 2020, displayed with yellow circles and green diamonds respectively.



Agronomic Results

Soybean yield was affected by site-year (p-value < 0.0001), though not by fertilizer treatment (p-value = 0.1377). In Figure 2, site-year mean yields for each treatment were compared to the control. Most of the points fell within 10% of the control, but for every treatment, points outside the 10% range occurred. No fertilizer treatment consistently impacted yields, but there was a significant interaction between treatment and site-year indicating that fertilizers may impact yield in different locations. Higher-yielding sites did not trend towards higher responses to nutrient applications, but throughout all analyses conducted, significance was not observed at any sites with yield below 54 bu/A.

Figure 2. Scatter plots of each fertilizer treatment against the untreated control at each specific site. The solid line plots the control, and the dotted lines indicate 10% above and below control yields. Points above the solid line indicate when soybeans treated with fertilizer yielded higher than the untreated control and points below indicate when the untreated control yield higher than the fertilized soybeans.



Linear modeling indicates that for every lb of N applied, an average of 0.013 bu/A grain yield increase was observed. Soybean yield response to S application was not significant among the three yield environments.

While N application rate was positively correlated with yield, the increase per lb of N was extremely slight, similar to previous research (Mourtzinis et al., 2018). Unlike previous research which stated that higher-yielding environments benefit from N fertility, an interaction between yield environment and N rate was not observed (Beard & Hoover, 1971; La Menza et al., 2017, 2019). This difference between our research and previous studies may be due to the low rates of N applied.

Table 2. Average yields for all treatments at sites where yield of one or more fertilizer treatments increased or decreased yield compared to the untreated control. Within each column, values with different letters are statistically different.

SOURCE	RATE	SITE – YEAR MEAN YIELD (bu/A)						
		EAST TROY, WI	MINNESOTA LAKE, MN	HANCOCK, WI	MINNESOTA LAKE, MN	PRINCETON, KY	GALESVILLE, WI	PLATTEVILLE, WI
		2019			2020			
CONTROL		75.4 ab	54.1 b	74.8 a	69.3 bc	68.4 b	75.3 ab	75.6 bc
AMS‡	LOW	78.5 a	64.9 ab	73.9 a	75.4 ab	75.4 ab	74.9 abc	88.7 ab
	MED.	74.3 abc	68.6 a	66.4 abc	75.8 a	70.3 ab	75.6 ab	87.3 ab
	HIGH	71.2 abc	65.0 ab	61.7 abc	74.4 ab	75.8 ab	73.9 abc	89.8 a
$CaSO_4$	LOW	67.7 bcd	67.0 a	69.2 ab	74.3 ab	73.2 ab	72.9 bc	83.9 abc
	MED.	59.5 d	66.3 a	60.9 abc	73.3 abc	73.0 ab	75.2 ab	83.0 abc
	HIGH	71.5 abc	67.1 a	68.0 ab	75.8 a	68.8 b	69.5 c	89.8 a
Urea	LOW	64.7 cd	62.2 ab	52.5 c	71.4 abc	78.7 a	78.8 a	72.8 c
	MED.	78.0 a	60.3 ab	56.2 bc	68.4 c	69.9 ab	75.8 ab	78.3 abc
	HIGH	75.0 ab	54.6 b	66.9 ab	70 bc	74.1 ab	77.3 ab	75.3 bc
†HSD α= 0.05		**9.9**	**10.9**	**14**	**5.6**	**9**	**5.7**	**13.7**

† Honest Significant Difference ‡ Ammonium sulfate

INDIVIDUAL SITE-YEAR ANALYSIS

Site-year-specific Fertilizer Treatment Effect on Yield

Fertilizer treatments increased yield when compared to the control at four sites (Minnesota Lake, MN in 2019; and Princeton, KY; Minnesota Lake, MN; Platteville, WI in 2020) while treatments lowered yield when compared to the control at three sites (East Troy, WI; Hancock, WI; in 2019 and Galesville, WI in 2020) (Table 2). Treatments of AMS increased yield at three sites (Minnesota Lake, MN, in 2019 and 2020 and Platteville, WI in 2020). Treatments of $CaSO_4$ increased yield at three sites (Minnesota Lake, MN, in 2019 and 2020 and Platteville, WI in 2020). and decreased yield at two sites (East Troy, WI in 2019 and Galesville, WI in 2020). Urea treatments increased yield at one site (Princeton, KY in 2020) and decreased yield at two sites (East Troy, WI and Hancock, WI in 2019).

Image 2. R1 developmental stage: the first instance of a soybean flower indicates the plant has transitioned into reproductive stages.

At Platteville, WI, yield trends were proportional to fertilizer rate applied, suggesting that rates higher than those applied in this study could be beneficial (Table 2). Despite this trend, synthesis analysis of 207 environments and studies with rates as high as 505 lb/A did not see positive yield response to higher N rate (Mourtzinis et al., 2018). Additionally, average S uptake has been documented at 14-17 lb/A, indicating that higher S application rates would not be used or taken up by the plant, but would remain in the soil (Bender et al., 2015; Gaspar et al., 2018; Salvagiotti et al., 2021).

These responses are consistent with previous studies which did not observe consistent responses to S additions (Borja Reis et al., 2021; Cannon et al., 2021; Letham et al., 2021; Moro Rosso et al., 2020; Roysdon, 2021). Although yield increases with fertilizer treatment were seen, no treatment was consistently higher than the control (Table 2). Notably, none of the AMS treatments significantly decreased yield compared to the control at any of the site-years.

Sulfur Cycling

Annual sulfur deposition for the site-years in the study averaged 2.1 lb/A. When this is compared with soybeans average uptake of 14 – 17 lb/A, a deficit of 12 – 15 lb/A arises, which must be provided through the soil or fertilizer (Bender et al., 2015; Salvagiotti et al., 2021). At the sites in our 2019-2020 trial, the average S concentration in the soils tested was 8.33 ppm. These soil samples were taken to a depth of 8 inches indicating that in the top 8 inches of soils in this study contained approximately 16 – 22 lb S/A depending on soil type. Currently, most soils contain adequate amounts of S to supply for soybean uptake needs.

Image 3. Urea fertilizers treatments, N treatments were used to measure the N impact when adding fertilizers which contain both N and S.

*Table 3. Treatment mean yields and partial profits at soybean grain price $8.72 and $14.98/bu for all site-years.**

SOURCE	RATE	MEAN YIELD (bu/A)	PARTIAL PROFITS AT SOYBEAN GRAIN PRICE OF $8.72/bu (US$/A)	PARTIAL PROFITS AT SOYBEAN GRAIN PRICE OF $15.00/bu (US$/A)
CONTROL		61.6	536.29	924.01
AMS‡	LOW	62.7	533.50	928.14
	MED.	62.7	526.01	920.49
	HIGH	63.3	524.35	922.87
$CaSO_4$	LOW	62.7	535.09	929.52
	MED.	61.8	522.14	911.09
	HIGH	61.9	517.46	906.91
Urea	LOW	61.9	529.71	919.11
	MED.	62.2	528.32	919.59
	HIGH	62.2	525.48	917.16

‡ Ammonium sulfate

**No significant differences within columns.*

Economic Results

Mean yield and partial profit for each treatment is available in Table 3. Profitability significantly varied between site-years (p-value < 0.0001).

Site-specific Fertilizer Treatment Effect on Partial Profits

Partial profit analysis was conducted on each of the site-years individually. When treatments were compared to the control, partial profit increases or decreases were observed at 5 site-years (Tables 4 and 5). At all other site-years, partial profits of all treatments were comparable to the control.

At the $14.98/bu soybean price, the same treatments increased or decreased partial profits when compared to the control, as with the previous analysis of the $8.72/bu price (Table 5). Additionally, at the higher soybean price, treatments of $CaSO_4$ at the medium and high rate also increased partial profits at the Minnesota Lake, MN, site in 2019.

Although linear yield increases due to N fertilizer were observed, they were only economically beneficial at one site-year (Tables 4 and 5), similar to what Salvagiotti et al. (2008) observed.

Table 4. Average partial profits at $8.72/bu soybean grain price for all treatments at sites where at least one or more fertilizer treatments increased or decreased yield compared to the untreated control. Values with different letters are statistically different, within columns.

SOURCE	RATE	SITE – YEAR US$/A				
		EAST TROY, WI	HANCOCK, WI	MINNESOTA LAKE, MN	PRINCETON, KY	GALESVILLE, WI
		2019	2019	2019	2020	2020
CONTROL		657 ab	651 a	471 bc	596 b	656 ab
AMS‡	LOW	671 a	631 ab	553 abc	645 ab	640 ab
	MED.	627 abc	558 abcd	577 a	593 b	638 ab
	HIGH	593 abc	511 bcd	539 abc	633 ab	617 bc
$CaSO_4$	LOW	579 bcd	592 abc	573 a	627 ab	624 bc
	MED.	502 d	515 bcd	561 ab	620 ab	639 ab
	HIGH	602 abc	570 abc	564 ab	577 b	584 c
Urea	LOW	554 cd	448 d	532 abc	676 a	678 a
	MED.	666 a	477 cd	512 abc	595 b	647 ab
	HIGH	637 abc	566 abcd	459 c	629 ab	657 ab
†HSD α= 0.05		**86**	**122**	**95**	**78**	**49**

† Honest Significant Difference ‡ Ammonium sulfate

Precipitation and Soil Environmental Factors Comparison of Responsive Site-years to Non-responsive Site-years

A consistent yield response to S applications was not observed across all site-years (Table 6). This is in agreement with a previous meta-analysis that also showed yield responses to S application depended on the environment (Borja Reis et al., 2021). The comparison of responsive sites to non-responsive sites seeks to identify what environmental factors may cause yield responses to S application (Table 6). The small number of responsive sites limits the strength of these findings. Despite these limited findings, notable observations can be made for future study.

The three site-years at which S treatments increased yield compared to the control were analyzed against the remaining 49 sites, and the four site-years at which N treatments increased yield compared to the control were analyzed against the remaining 48 sites (Table 6). Sites with higher yield in plots fertilized with S had lower soil test phosphorous levels (p-value = .0001). Similarly, site-years with a positive yield response to N additions also had lower phosphorous mean values when compared to sites without a positive response (p-value = <.0001). Site-years where plots with S fertilizer had higher yield than the untreated control had significantly less precipitation and S deposition than site-years without a significant response

Table 5. Average partial profits at $14.98/bu soybean grain price for all treatments at sites where at least one or more fertilizer treatments increased or decreased yield compared to the untreated control. Values with different letters are statistically different, within columns.

SOURCE	RATE	EAST TROY, WI (2019)	HANCOCK, WI (2019)	MINNESOTA LAKE, MN (2019)	PRINCETON, KY (2020)	GALESVILLE, WI (2020)
		SITE – YEAR US$/A				
CONTROL		1131 ab	1122 a	812 b	1026 b	1130 ab
AMS‡	LOW	1165 a	1096 ab	962 ab	1119 ab	1111 ab
	MED.	1095 abc	976 abcd	1009 a	1036 b	1114 ab
	HIGH	1042 abc	899 bcd	948 ab	1110 ab	1082 bc
$CaSO_4$	LOW	1004 bcd	1028 abc	995 a	1088 ab	1083 bc
	MED.	877 d	898 bcd	979 a	1080 ab	1113 ab
	HIGH	1052 abc	998 abc	986 a	1011 b	1021 c
Urea	LOW	962 cd	778 d	924 ab	1171 a	1174 a
	MED.	1157 a	830 cd	892 ab	1035 b	1123 ab
	HIGH	1109 abc	987 abcd	803 b	1096 ab	1143 ab
†HSD α= 0.05		**148**	**210**	**164**	**134**	**85**

† Honest Significant Difference ‡ Ammonium sulfate

(p-value = 0.0085 and 0.0116 respectively). But, site-years where plots with S fertilizer had significantly lower yield than the untreated control also had significantly less precipitation and S deposition than site-years without yield differences (p-value = 0.0008 and 0.0451, respectively). Since S deposition occurs via rainfall it is not surprising that both precipitation and S deposition were lower in responsive site-years (Table 6). Because both precipitation

Table 6. Comparison of precipitation and soil environmental factors for sites positively responsive to S and N compared against unresponsive sites.

		PRECIPITATION in/yr	SULFUR DEPOSITION lb/A/yr	NITROGEN DEPOSITION lb/A/yr	pH	OM %	P ppm	K ppm	S ppm
SULFUR									
POSITIVE RESPONSE	MEAN	42.2	1.6	11.4	6.2	4.5	18.7	131	15.1
NO OR NEGATIVE RESPONSE	MEAN	48.5	2.1	8.1	6.4	2.5	58.9	138	7.9
	***P*-value**	**0.0085**	**0.0116**	**0.1342**	**0.5031**	**0.1048**	**0.0001**	**0.6154**	**0.679**
NITROGEN									
POSITIVE RESPONSE	MEAN	46.7	2.0	10.5	6.1	3.8	17.8	202	15.7
NO OR NEGATIVE RESPONSE	MEAN	48.2	2.1	8.1	6.4	2.6	59.8	133	7.62
	***P*-value**	**0.7699**	**0.9073**	**0.1658**	**0.2067**	**0.2301**	**<0.0001**	**0.4055**	**0.3956**

and S deposition were significant it is difficult to determine which, or both, is related to the yield response. Further research is necessary to determine if S response is related to precipitation, S deposition, both, or another factor occurring in these environments. Full methods for these environmental comparisons can be found in the full publication, which is available at: https://doi.org/10.1002/agj2.21216

Recommendations

Purely S applications increased yield in 3 of 52 environments. Yield responses to sulfur application (with or without N application) only occurred in yield environments at or above 54 bu/A. In the future, as soybean yields continue to increase and S deposition continues to decrease, S in soils may be depleted and S additions may prove to be more profitable. At present, based on this study and the current body of agronomic publications, in most environments, S available via atmospheric deposition and supplied via soil cycling provides sufficient S for optimal growth.

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