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Optimizing sulfur fertilizer application rate for profitable maize production in the savanna agroecological zones of Northern Ghana

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ABSTRACT

Although several studies have established the importance of sulfur (S) in increasing maize productivity in the savanna agroecological zones (AEZs) of northern Ghana, the economically optimum S application rate is still unknown. In a two-year study at eight locations across the AEZs, we determined the economically optimum S application rate for S-deficient soils. We compared eight S application rates, ranging from 0 to 70 kg ha⁻¹ at 10 kg intervals, for optimal maize productivity and profitability. The study identified 30 kg S ha⁻¹ as the minimum rate that resulted in a plant tissue S concentration above the critical level of 0.15%. Although increasing the S application rate resulted in increases in maize grain yield, application of S beyond a rate of 30 kg ha⁻¹ resulted in increases in maize grain yield that were not statistically significant and leveled off at 50 kg S ha⁻¹. Application rates ≥ 50 kg ha⁻¹ resulted in a high proportion of the applied S not taken up by the plant and, thus, subject to losses from the soil. Based on agro-input prices at the local level and the farm-gate prices of maize, the greatest potential profit resulting from S application was observed at 30 kg S ha⁻¹, with a projected average maize yield of between ~ 4.2 and 5.3 Mg ha⁻¹, representing $>90\%$ of the observed yield with the highest S application rate of 70 kg ha⁻¹. Thus, we conclude that, for sustainable and profitable maize production in S-deficient soils of the savanna AEZs of northern Ghana, an S applications rate of 30 kg ha⁻¹ is economically justified.

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Apparent nitrogen recovery efficiency; apparent sulfur recovery efficiency; economically optimum fertilizer rate; maize yield; Mitscherlich equation; tissue sulfur concentration

Introduction

Maize is a crop that requires high levels of essential plant nutrients for increased productivity. In addition to macronutrients (nitrogen [N], phosphorus [P], and potassium [K]), secondary and micronutrients play a role in increasing maize yield in the savanna agroecological zones (AEZs) of northern Ghana, which has been well established (Kugbe, Kombat, and Atakora 2019). However, unlike N and P, sulfur (S) has not been studied extensively in much of the savanna AEZs of northern Ghana because S deficiencies have seldom been documented. However, several studies have shown that S is critical for maize production, particularly for the newly evolved high-yielding maize hybrids and open-pollinated varieties (Sutar et al. 2017; Kaur et al. 2019).

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Kovar (2021) observed that S deficiency symptoms in maize are difficult to detect because they are not always obvious, and if detected, it is expensive to correct during the growing season. However, studies by several workers in many parts of the world, involving several agroecological regions have shown significant maize yield responses with S application (Khan et al. 2006; Kanton et al. 2016; Kaur et al. 2019; Kugbe, Kombat, and Atakora 2019; Garba et al. 2020). Kaur et al. (2019) and Kugbe, Kombat, and Atakora (2019) reported that in S-deficient soils, the use efficiency of applied NPK fertilizers and the economics of their use are seriously affected, resulting in non-attainment of anticipated high yields and profitability. Thus, the complete yield potential of the high-yielding maize cultivars cannot be obtained when soils are deficient in S, irrespective of whether all other essential nutrients are in adequate supply and excellent farm management practices are followed.

Sulfur not only influences yield but also improves crop quality due to its influence on protein metabolism and oil synthesis (Krishnamoorthy 1989; Patil et al. 1998). In maize, important quality parameters, such as carbohydrate and protein yields, are affected by the level of S supply. Sulfur also improves the quality of crops because it has a direct impact on the various biochemical reactions in plants and participates in chlorophyll formation. Several studies have shown that S is involved in the synthesis of essential amino acids, such as cystine and methionine (Singh 2001; Kumar and Yadav 2007). In addition, it is a constituent of the vitamins: thiamin and biotin, S-glycosides, and coenzyme A. It improves crop management through its favorable effects on environmental stress and resistance against pests and diseases (Rausch and Wachter 2005; Kruse et al. 2007). Sulfur encourages photosynthetic activity by increasing chlorophyll pigments, synthesis of essential amino acids and proteins, and translocation and utilization of starch and nitrogen; all of these functions consequently converge to increase maize yield.

Reports on the S application rate to achieve optimal maize productivity have not been consistent across the savanna agroecological zones of SSA. Most farmers in the savanna AEZs of northern Ghana have adopted an S application rate of 50 kg ha⁻¹ for maize production, although the basis for that recommendation is unknown. For sustainability and to obtain the maximum benefit from investments in S fertilizers, and fertilizer in general, the rate must be economically justified; however, to our knowledge, no study has specifically evaluated S application rates in northern Ghana that will optimize not only maize yield, but also potential profitability of S fertilizer use. Therefore, the main objective of this study was to determine the economically optimum S fertilizer application rate for S-deficient soils of the savanna AEZs of northern Ghana. Specific objectives were to determine: (i) yield responses of maize to different S application rates, and (ii) economically optimum S rate for maize production under the prevailing price combinations of S fertilizer and maize, based on unsubsidized local agro-input market and farm-gate prices.

Materials and methods

Experimental sites

The trials were conducted during the 2018 and 2019 farming seasons in eight communities in northern Ghana: four each in the Guinea Savanna and Sudan Savanna AEZs. Sulfur-deficient soils were specifically selected for the trials at all locations. The trials in the Guinea Savanna AEZ were located at Damango (9°05'36.9"N 1°49'05.0"W), Karaga (9°55'32.7"N 0°25'45.7"W), Wechiau (9°48'46.3"N 2°40'47.8"W), and Zabzugu (9°17'49.3"N 0°22'08.3"E); those in the Sudan Savanna AEZ were located at Binaba (10°48'08.6"N 0°28'19.6"W), Bunkpurugu (10°30'47.8"N 0°06'10.6"E), Issa (10°23'32"N 2°19'57"W), and Sandema (10°44'35.1"N 1°17'32.7"W). A map showing the locations of the experimental sites is presented in Figure 1. The soil in the entire region is classified as Savanna Ochrosols (Brammer 1962) but has different chemical characteristics among experimental sites, fitting into the World Reference Base classification of either

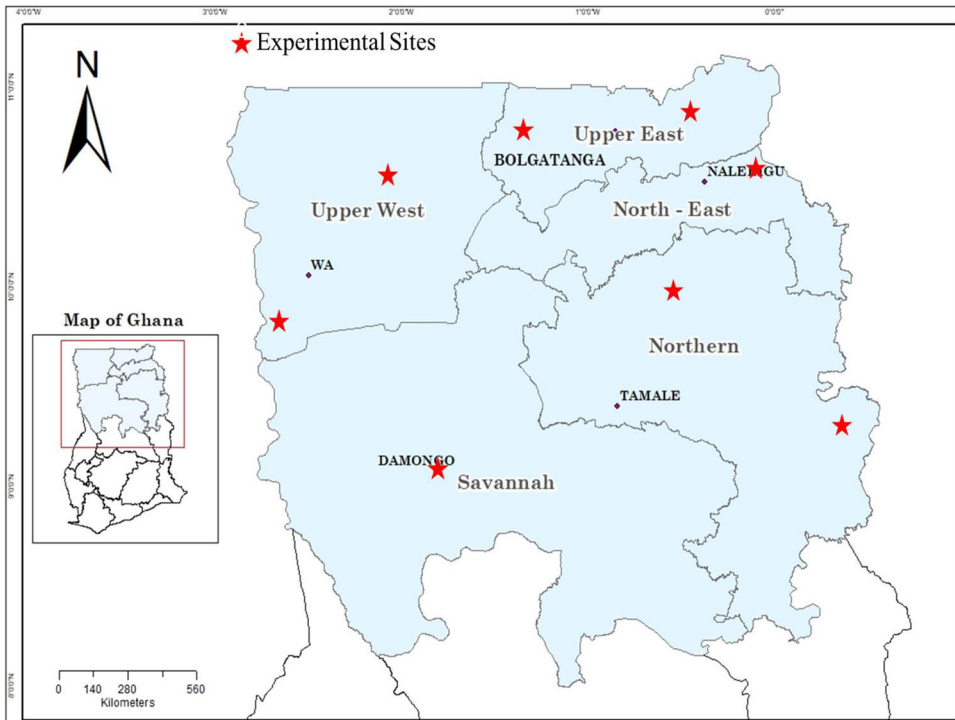


Figure 1. Map of northern Ghana showing the locations of the experimental sites.

Lixisols, Luvisols, or Plinthosols (ISSS/ISRIC/FAO 1998). Seasonal rainfall amount ranges from 900 mm to 1,400 mm in a mono-modal distribution at all locations, and temperature ranges from 31° to 32°C (Guinea Savanna AEZ) and 32° to 33°C (Sudan Savanna AEZ). The growing season is between five and six months (May–October) in the Guinea Savanna AEZ and four to five months in the Sudan Savanna AEZ (Figure 2), followed by dry conditions until the next rainy season (Issahaku, Campion, and Edziyie 2016).

Characterization of initial soil conditions

Before starting the trials, composite surface soil samples were collected from each site to determine the initial soil conditions. Each field was divided into 16 subunits, and a composite soil sample (formed by mixing twenty 25-mm-diameter core samples) was collected from the top 30 cm of each subunit. Air-dried soil samples were analyzed for the initial soil chemical properties (Table 1) according to the methods described in Agyin-Birikorang et al. (2020). Soil pH was determined in water (1:2 soil-to-water ratio), organic carbon by chromic acid titration, available P by Bray-1 extraction, exchangeable K, calcium (Ca), and magnesium (Mg) by ammonium acetate extraction, and plant-available S by monocalcium phosphate extraction. Calcium phosphate extracts were analyzed via inductively coupled plasma-atomic emission spectroscopy (SPECTRO Analytical Instruments GmbH, Kleve, Germany) to account for both $\text{SO}_4\text{-S}$ and dissolved organic S (Zhao and McGrath 1994).

Field layout and experimental setup

The treatments for the study consisted of eight S fertilizer application rates: 0 (control), 10, 20, 30, 40, 50, 60, and 70 kg S ha^{-1} . The experiment was laid out in a randomized complete block

design (RCBD), with each of the eight treatments having four replications and each treatment randomly assigned to a plot within each block. Individual plot size was 8.1 m x 5 m. All limiting essential nutrients, based on a soil fertility map developed for the AEZs (IFDC, unpublished data), were supplied in adequate quantities such that only S remained the limiting nutrient. N, P, K, zinc (Zn), and boron (B) were applied at uniform rates of 100 kg N ha⁻¹ (in ammonium sulfate [21% N] and ammonium nitrate [34% N]), 40 kg P ha⁻¹ (in TSP [45% P₂O₅]), 60 kg K ha⁻¹ (in KCl [62% K₂O]), 5 kg Zn ha⁻¹ (ZnCl₂ [50% Zn]), and 1 kg B ha⁻¹ (Borax [11% B]), respectively, to all treatments. Zn and B were applied in solution to ensure uniform distribution across each plot. Except for N, which was split-applied, all nutrients were applied in full doses at planting. The local extension practice for the region is for N to be applied in two splits: one-half at planting and one-half at V6 stage (~42-46 days after emergence). However, for this study, a slight modification was made to the extension recommendation of the splits N application: Since the S fertilizer source (ammonium sulfate) contained both N and S, it was applied at quantities to supply the required S per treatment, and the shortfall in the N requirement was supplied with ammonium nitrate. That is, applying the highest S rate (70 kg S ha⁻¹) from ammonium sulfate supplied 61 kg N ha⁻¹. Therefore basal N for all treatments was applied at this rate, and the shortfall in basal N occurring with lower S application rates was supplied with ammonium nitrate, with all treatments receiving a basal N application of 61 kg ha⁻¹. The remainder of the required N (39 kg ha⁻¹) was applied at V6 stage.

A high-yielding, medium-maturing (115 days), and drought-tolerant maize hybrid (*Pan 53*) was used as the test crop for both years. The seeds were planted with an inter-row spacing of 80 cm and an intra-row spacing of 20 cm with one plant per hill, resulting in a plant population of 62,500 plants ha⁻¹. Planting was done at the onset of the rains at the various locations (commencing in mid-June to mid-July in both years (Figure 2)). All other management practices, including weed, pest (particularly fall armyworm), and disease control, were carried out judiciously when required.

Determination of maize yield, tissue nutrient concentration, and uptake

At the initial silk stage, ear leaves were collected from 10 plants randomly selected from the four center rows of each plot to determine the S concentration of the plants. The samples were digested by the dry ashing method as described by Jones and Case (1990), and S content was measured using Spectro Arcos ICP-OES analyzer (SPECTRO Analytical Instruments GmbH, Kleve, Germany). At physiological maturity, the four center rows of each plot were manually harvested, de-husked, and shelled. The grains were weighed, and the moisture content was measured to determine grain yield. All grain yields were adjusted to a moisture content of 15.5% (Agyin-Birikorang et al. 2020) to ensure uniform treatment comparison. Plant biomass samples were collected by manually harvesting 12 plants randomly selected from the rows immediately outside the four center rows. Subsamples were weighed and oven-dried at 65 °C (until the weights became stable) to calculate biomass weights. Samples of the harvested grain and biomass were oven-dried, ground, and digested to determine tissue S and N concentrations. Total N in grain and biomass was determined using a micro-Kjeldahl method, a modification of the aluminum block digestion technique described by Gallaher et al. (1975), followed by automated colorimetry with a Technicon Auto Analyzer. Grain and biomass S content was determined as described above. The product of S and N concentrations and total biomass (grain + stover yield) was used to calculate the uptake of the respective nutrients per plot. Apparent S and N recovery efficiency (AR [%]) was calculated following the procedure described in Dobermann and Cassman (2005):

$$AR = \frac{(Sf - S0)}{SA} \times 100$$

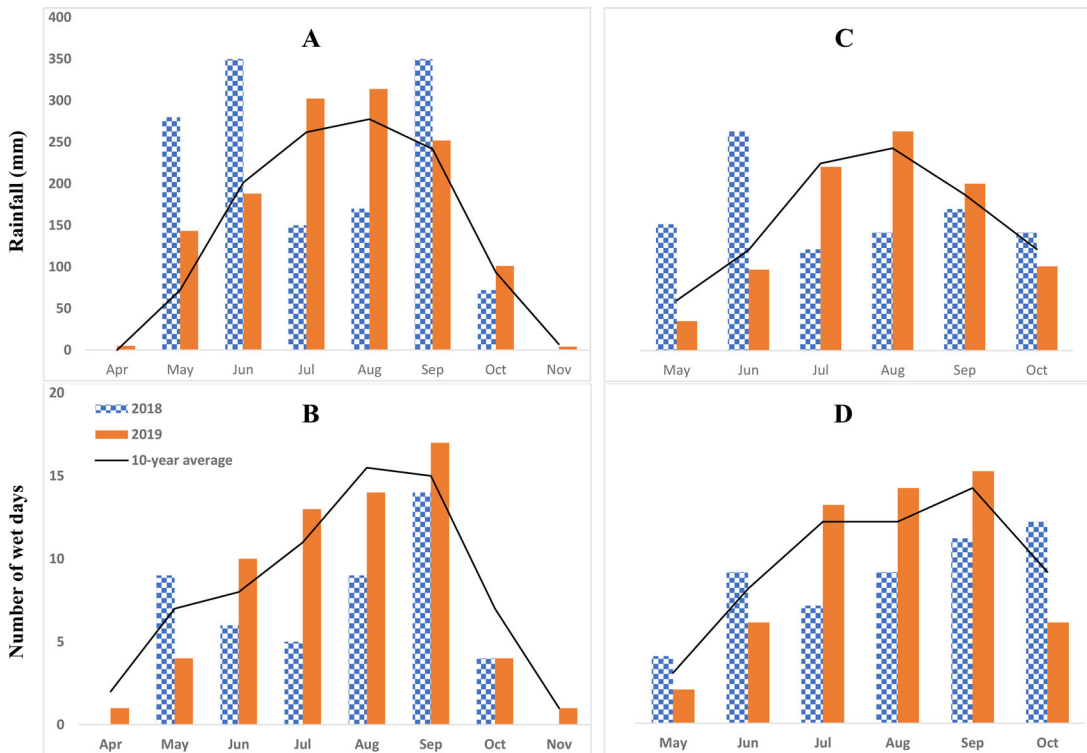


Figure 2. Rainfall distribution in northern Ghana during the 2018 and 2019 growing seasons and 10-year average rainfall showing: (A) rainfall amounts in the Guinea Savanna AEZ, (B) number of wet days in the Guinea Savanna AEZ, (C) rainfall amounts in the Sudan Savanna AEZ, and (D) number of wet days in the Sudan Savanna AEZ. Source: Modified from Agyin-Birikorang et al. (2022).

where S_f is either S or N accumulation in the aboveground plant dry matter resulting from S fertilizer application (kg ha^{-1}), S_0 is S or N accumulation in aboveground plant dry matter resulting from the control (no S) (kg ha^{-1}), and SA is the quantity of either S or N applied from fertilizer (kg ha^{-1}).

Post-harvest soil sampling and analysis

After the final harvest in each growing season, soil samples were collected and analyzed for S and N concentrations, as described above for S and in Agyin-Birikorang et al. (2020) for N, to determine residual S and N contents of the soil as influenced by S application rate and to calculate the S and N balance for each treatment.

Determination of economically optimum sulfur application rates

Analyses of yield response model and economically optimum fertilizer rates were carried out following a modification of the procedure described by Valkama, Uusitalo, and Turtola (2011). Yield response to S rates was analyzed using the Mitscherlich yield response model, a statistical model commonly used to describe the relationship between fertilizer rates and yield responses (Schabenberger and Pierce 2002). The Mitscherlich model was expressed in the form:

$$y = a(1 - e^{-bx})$$

where y is the yield response, a is the maximum yield, b is the constant that governs the rate of yield response (steepness of the yield response curve), and x is the S fertilizer rate.

The Marquardt–Levenberg algorithm was used to find the coefficients (parameters) of the independent variables that give the best fit between the equation and the data using the SigmaPlot 14.5 program (SYSTAT Software Inc., San Jose, CA, USA). This algorithm seeks the values of the parameters that minimize the sum of the squared differences between the observed and predicted values of the dependent variable. The Shapiro–Wilk test was used to determine whether the weighted residuals (observed yield increase–estimated yield increase) of the model were normally distributed using the SYSTAT software. The economically optimum S rate was calculated based on the expected profit from the S application, which was derived using a modification of the calculation described in McConnell and Dillon (1997):

$$\text{Profit (GH¢ ha}^{-1}\text{)} = \text{Yield Increase due to S Fertilization (kg ha}^{-1}\text{)} \times$$

$$\text{Yield Value (GH¢ kg}^{-1}\text{)} - \text{Applied S (kg ha}^{-1}\text{)} \times \text{S Fertilizer Price (GH¢ kg}^{-1}\text{)}$$

Note: 1 Ghana cedi (GH¢) = U.S. \$0.174

The unsubsidized input costs from the local market and farm-gate maize prices were obtained from the Esoko database (Esoko 2021).

The profit from S application was considered optimal when the difference between the extra income due to the yield increase and the cost of the S fertilizer used was at its highest (positive) value. The average value of the yield increase term was obtained from the least-squares fits of the Mitscherlich response curves, and its range was calculated on the basis of the standard error of the variable a (maximum yield) of the curves.

Statistical analyses

First, analysis to assess treatment and experimental site effects and their interactions was conducted using a mixed analysis of variance (ANOVA), in which all the factors and their interactions were handled as fixed effects and the residual, or error, term as a random effect. A second analysis to test the effect of growing season (year) was conducted with an ANOVA mixed model containing the factors enumerated above plus the year. In this second model, the random factor was the residual term. The ANOVA model assumption of normality and homogeneity of variances were tested using the Kolmogorov–Smirnov procedure and Levene’s test residual plots, respectively (Littell et al. 1996). ANOVA for grain yield, tissue S concentration, aboveground S and N uptake, and apparent S and N recovery efficiency was performed using a generalized linear mixed model (PROC GLIMMIX, SAS 9.4) (SAS Institute Inc 2018), in which treatments and growing season, as well as their interactions, were handled as fixed effects, while replications and their interactions were handled as random effects (Littell et al. 1996). Differences in mean values of the various parameters among treatments were separated using Tukey’s Honestly Significant Difference (HSD) test, which corrects for the experiment-wise error rate (Littell et al. 1996). The trends of the increasing S rate effects for each of the measured parameters were assessed using polynomial contrasts (Littell et al. 1996).

Results

Physicochemical characteristics of soil at experimental sites

The texture of the soil at the experimental sites were either sandy loam (Bunkpurugu, Damango, Issa, Wechiau, and Zabzugu) or coarse-textured loam (Binaba, Karaga, and Sandema) (Table 1). The soil in the various experimental sites were weakly acid to near-neutral, with pH ranging from 6.04 (Damango) to 6.44 (Karaga) (Table 1). Across all experimental sites, the soils were low in organic C content, having values < 0.5%, and low in plant-available P (<3 mg kg⁻¹), and S

Table 1. Selected chemical properties of the soils used for the trials at the various sites.

Site	pH-H ₂ O	Organic C (g kg ⁻¹)	Available P mg kg ⁻¹	SO ₄ -S	Exchangeable cations			Texture		
					K	Ca cmol kg ⁻¹	Mg	Sand	Silt g kg ⁻¹	Clay
Binaba	6.27	4.66	1.16	0.93	0.15	1.68	0.79	520	330	150
Bunkpurugu	6.19	3.76	2.98	1.21	0.15	1.32	0.41	560	280	160
Damango	6.04	4.65	3.87	1.23	0.16	1.17	0.31	570	310	120
Issa	6.40	3.62	2.91	1.01	0.11	1.27	0.77	550	310	140
Karaga	6.44	4.50	1.44	1.24	0.18	1.18	0.79	520	320	160
Sandema	6.36	3.58	2.72	1.06	0.19	1.35	0.88	510	350	140
Wechiau	6.23	2.68	2.24	1.01	0.11	1.00	0.58	540	290	170
Zabzugu	6.09	3.30	2.95	1.25	0.13	1.48	0.54	570	290	140

Numbers are mean values of 16 replicates.

(<1.3 mg kg⁻¹), and low to moderate exchangeable K (0.11 – 0.19 cmol kg⁻¹), Ca (1.0 – 1.7 cmol kg⁻¹) and Mg (0.3 – 0.9 cmol kg⁻¹).

Ear-leaf tissue sulfur concentration

Averaged across all locations, increasing S application rates resulted in increasing ear-leaf tissue S concentrations, with mean values of 0.032%, 0.064%, 0.115%, 0.1531%, 0.171%, 0.194%, 0.212%, and 0.22% for the 0 (control), 10, 20, 30, 40, 50, 60, and 70 kg ha⁻¹ treatments, respectively, during the 2018 growing season (Figure 3). Similarly, in the 2019 growing season, tissue S concentrations averaged across all experimental sites were 0.034%, 0.072%, 0.121%, 0.171%, 0.204%, 0.222%, 0.241%, and 0.244% for S application of 0 (control), 10, 20, 30, 40, 50, 60, and 70 kg ha⁻¹, respectively (Figure 3).

Maize grain yield

At all experimental sites, there were highly significant effects of S application rate and growing season on maize grain yield. However, the interaction effect of the S application rate and growing season on maize grain yield was not significant. In general, maize grain yield obtained during the 2019 growing season was significantly higher than that of the 2018 growing season across all experimental sites. However, regardless of the differences in maize yield between the two growing seasons, the treatment effects on maize yield followed a similar pattern for each growing season. Across all experimental sites, the lowest yield occurred with the control. Application of S increased maize yield; the highest yield occurred with an application rate of 70, 60, 50, 40, and 30 kg S ha⁻¹, followed by 20 kg S ha⁻¹, 10 kg S ha⁻¹ and 0 kg S ha⁻¹, in that order. Thus, across all experimental sites and for the two growing seasons, maize grain yield followed the order: 70 kg S ha⁻¹ = 60 kg S ha⁻¹ = 50 kg S ha⁻¹ = 40 kg S ha⁻¹ = 30 kg S ha⁻¹ > 20 kg S ha⁻¹ > 10 kg S ha⁻¹ > control. Although increasing the S application rate resulted in increases in maize grain yield, the increases were not statistically significant beyond 30 kg ha⁻¹ and leveled off at rates ≥50 kg S ha⁻¹ (Figure 4).

Aboveground sulfur uptake and apparent recovery efficiency

There was no significant location variation on aboveground S uptake, and therefore, S uptake was averaged across all experimental sites. However, there was a significant year effect on S uptake from the treatments, but the interactive effects of treatments and year on S uptake and apparent recovery efficiency were not significant. As a result, the S uptake data were analyzed separately for each growing season (Table 2). In both growing seasons, there was a highly significant

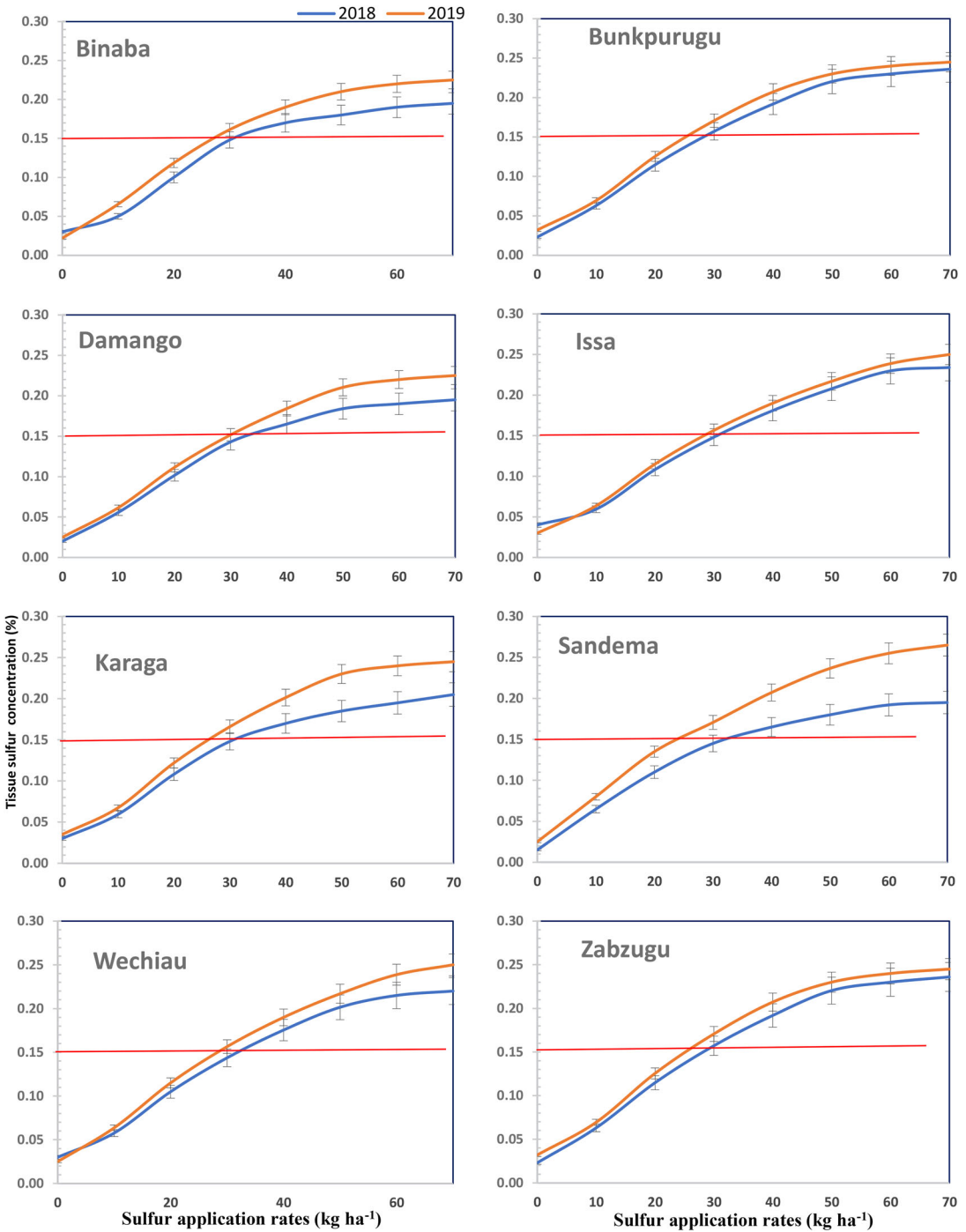


Figure 3. Ear-Leaf tissue sulfur concentration as a function of sulfur application rate. Error bars denote standard error of the mean. Horizontal line within the graph is a visual representation of the critical plant tissue sulfur concentration for maize.

positive correlation ($r=0.81$) between S application rate and aboveground S uptake, with increasing S application rates resulting in increased S uptake.

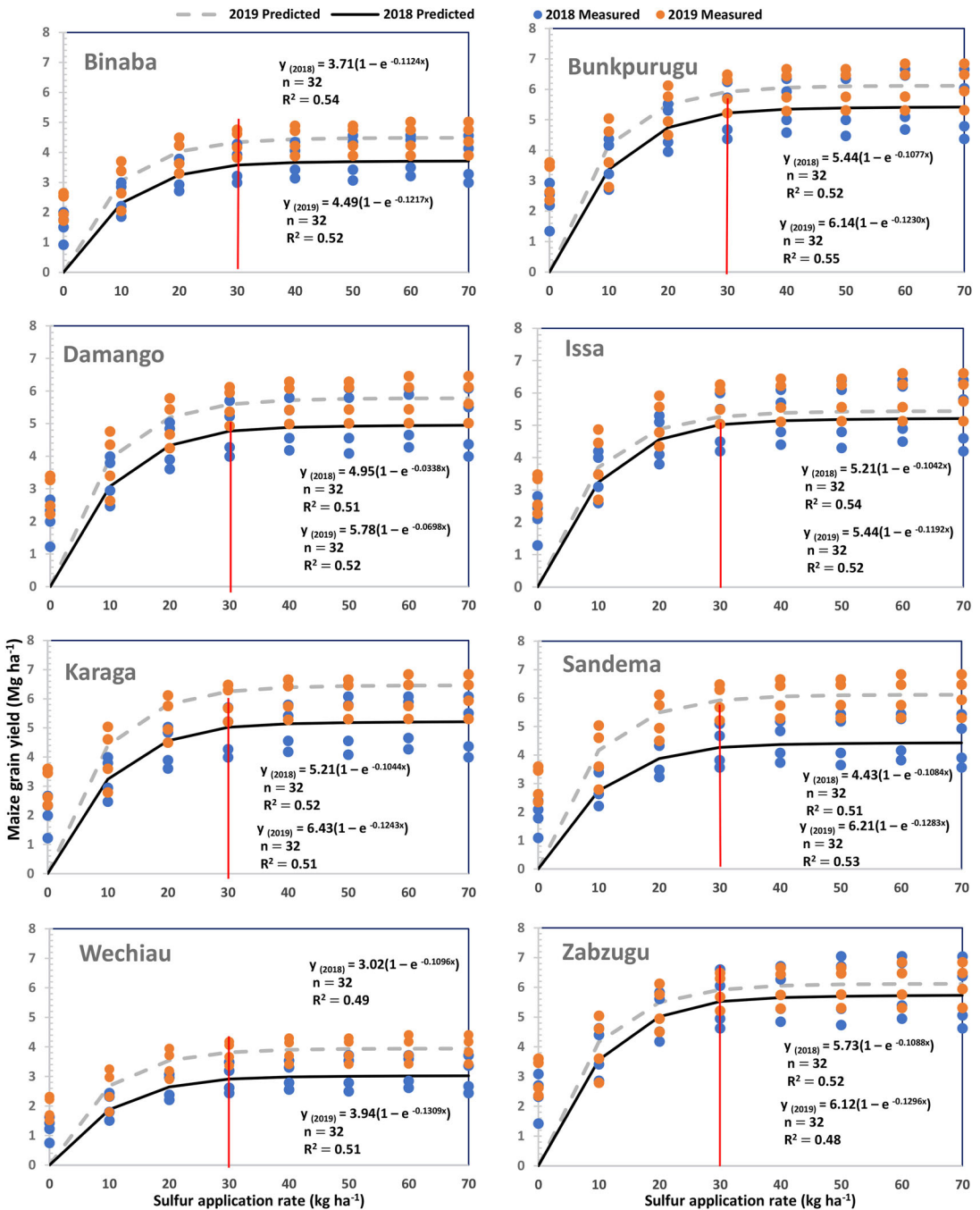


Figure 4. Maize grain yield as a function of sulfur application rate. Each dot represents measured yield for each plot. Vertical line indicates the predicted economically optimum sulfur application rate for each year.

In the 2018 growing season, the greatest aboveground S uptake occurred with the highest application rate of 70 kg S ha⁻¹, followed by 60, 50, 40, 30, 20, 10, and 0 kg S ha⁻¹, in that order. A similar trend of S uptake pattern was observed for the 2019 growing season (Table 2). Conversely, apparent S recovery efficiency decreased with an increasing S application rate. In the 2018 growing season, the greatest apparent S recovery efficiency of 80% was observed with the

Table 2. Aboveground sulfur uptake and apparent sulfur recovery efficiency of maize fertilized at different sulfur application rates during the 2018 and 2019 growing seasons.

Sulfur application rate (kg S ha ⁻¹)	Sulfur uptake (kg ha ⁻¹)		Apparent sulfur recovery efficiency (%)	
	2018	2019	2018	2019
0 (control)	0.45h	0.51h	N/A	N/A
10	8.42g	9.24g	79.2a	86.7a
20	13.8f	15.6f	67.3b	75.4b
30	17.3e	18.3e	57.2c	58.6c
40	20.6d	21.2d	50.1d	52.4d
50	21.7c	23.1c	41.6e	44.5e
60	22.8b	24.8b	37.3ef	40.1ef
70	25.2a	26.1a	35.4f	37.3f
Tukey's HSD (0.05)	1.02	1.18	6.01	5.86

Numbers are mean values of 32 replicates (8 sites x 4 reps/site), presented in three significant figures. Numbers in each column followed by the same letter are not significantly different ($p > 0.05$).

Table 3. Aboveground nitrogen uptake and apparent nitrogen recovery efficiency of maize fertilized at different sulfur rates during the two-year duration of the study.

Sulfur application rate (kg ha ⁻¹)	Nitrogen uptake (kg ha ⁻¹)		Apparent nitrogen recovery efficiency (%)	
	2018	2019	2018	2019
0 (control)	2.40h	3.14h	N/A	N/A
10	22.7g	29.5g	20.1d	25.4d
20	38.4f	49.1f	36.2c	46.4c
30	44.8e	54.1d	41.6c	50.5c
40	54.5d	67.8c	52.2b	65.4b
50	56.6c	74.2b	54.1ab	73.2ab
60	59.4b	76.8b	57.1ab	72.4ab
70	66.4a	81.1a	61.5a	77.5a
Tukey's HSD (0.05)	2.04	3.89	8.75	8.92

Numbers are mean values of 32 replicates (8 sites x 4 reps/site), presented in three significant figures. Numbers in each column followed by the same letter are not significantly different ($p > 0.05$).

lowest S application rate (10 kg S ha⁻¹), while the smallest apparent S recovery efficiency of 35% occurred with the highest S rate of 70 kg ha⁻¹ (Table 2). Similarly, in the 2019 growing season, the greatest S recovery efficiency of 87% and the lowest of 37% occurred with the 10 and 70 kg ha⁻¹ treatments, respectively. Thus, in both years, apparent S recovery efficiency followed the order: 10 kg S ha⁻¹ > 20 kg S ha⁻¹ > 30 kg S ha⁻¹ > 40 kg S ha⁻¹ > 50 kg S ha⁻¹ > 60 kg S ha⁻¹ = 70 kg S ha⁻¹ (Table 2).

Aboveground nitrogen uptake and apparent recovery efficiency

Similarly to S uptake, there was no significant location variation on aboveground N uptake, and as with S uptake, the aboveground N uptake was averaged across all experimental sites. Also, there was a significant year effect on N uptake resulting from S application rates but no significant location x year interaction. Therefore, N uptake data were collated separately for each growing season (Table 3). In both growing seasons, there was a significant positive correlation between S application rate and aboveground N uptake, with increasing S application rates resulting in increased N uptake. In the 2018 growing season, the greatest aboveground N uptake occurred with an application rate of 70 kg S ha⁻¹ and the smallest with the control. A similar trend for N uptake was observed for the 2019 growing season (Table 3). Contrary to the trend of apparent S recovery efficiency, which decreased with an increasing S application rate, apparent N recovery efficiency increased with an increasing S application rate. In the 2018 growing season, the greatest apparent N recovery efficiency of 62% occurred with the highest S application rate (70 kg ha⁻¹), while the lowest apparent N recovery efficiency of 20% occurred with the lowest S

Table 4. Residual soil sulfate-S and inorganic nitrogen ($\text{NO}_3\text{-N} + \text{NH}_4\text{-N}$) concentrations measured at the end of each growing season for the duration of the study.

Application rate (kg S ha^{-1})	Residual soil $\text{SO}_4\text{-S}$ concentration (mg kg^{-1})		Residual soil inorganic N concentration (mg kg^{-1})	
	2018	2019	2018	2019
0 (control)	0.34	0.41	2.92	2.77
10	0.39	0.44	2.85	3.01
20	0.43	0.42	3.12	3.14
30	0.44	0.44	2.99	2.96
40	0.37	0.51	3.04	2.93
50	0.34	0.47	3.24	3.05
60	0.44	0.46	2.98	2.74
70	0.42	0.46	3.22	3.17
Tukey's HSD (0.05)	0.13	0.12	0.82	0.67

Numbers are mean values of 32 replicates (8 sites x 4 reps/site), presented in three significant figures. Numbers in each column are not significantly different ($p > 0.05$)

application rate of 10 kg ha^{-1} (Table 3). Similarly, in the 2019 growing season, the greatest N recovery efficiency of 78% and the lowest of 26% occurred in treatments receiving 70 and 10 kg ha^{-1} , respectively (Table 3).

Residual sulfur and nitrogen concentrations

Across all experimental sites, residual soil S concentration values observed during the 2018 and 2019 growing seasons were not significantly different among respective treatments (Table 4). There were no significant differences in the residual soil S concentrations among the S application rates and the control. A similar trend was observed for residual soil N concentrations, with no significant differences among treatments for each growing season across all experimental sites, and the value observed for the control was not significantly different from those observed for S application treatments in respective growing seasons (Table 4).

Discussion

Effect of soil characteristics and weather conditions on sulfur application rate for maize production

Soils at the experimental sites had textures that are generally characterized by good drainage, limited susceptibility to compaction, and low to moderate water and nutrient holding capacity. The pH of the soils was (6-6.5) conducive for maize production, however, the soils were low in SOM content and low fertility status: deficient in plant-available P and S, and low to moderate exchangeable K, and Ca and Mg. Therefore, to increase maize productivity in such soils, and to realize the full benefits of investments in fertilizers, farmers must supply these limiting essential plant nutrients to their crops. Again, efforts must be made by farmers to conserve organic matter in the soil to improve the physical and chemical properties of the soil, such as water and nutrient holding capacity, and cation exchange capacity of the soils.

The rainfall pattern encountered during the two growing seasons provided a unique opportunity to evaluate the effect of S application rates on maize productivity under varying rainfall distribution patterns. Compared to the 10-year average, the 2018 growing season experienced a relatively higher total rainfall for the two savanna AEZs in northern Ghana (Figure 2a and c). However, the rainfall was not evenly distributed throughout the growing season, with much of it occurring during the months of June and July when the seedlings had just emerged and were too small to utilize all of the basally applied fertilizer nutrients. To exacerbate the problem, fewer wet days occurred during this period than the 10-year average (Figure 2b and d). This indicates that

rainfall intensity was higher than normal during this period, which resulted in excessive nutrient losses through leaching and/or surface runoff. Surprisingly, during the months of August and September, when peak rainfall was expected to occur for tassel initiation and grain filling, a short dry spell occurred that clearly affected maize productivity. On the other hand, although the total amount of rainfall during the 2019 growing season was lower than that of 2018, the pattern mimicked that of the 10-year average: rainfall was evenly distributed throughout the growing season, with a short dry spell toward the end of the growing season when the maize crops were nearing physiological maturity (Figure 2). Thus, the 2019 growing season had a better rainfall distribution pattern for maize production than the 2018 growing season.

Effect of sulfur application rate on sulfur sufficiency level for maize

The soil tests commonly used to determine plant-available S usually measure only the amount of $\text{SO}_4\text{-S}$ present in the sampled area but do not account for possible contributions from other potential sources, such as organic S mineralization and rainfall. Therefore, a high S soil test result indicates a possible adequate S supply, but a low test result could mean either S is inadequate or could possibly become adequate in course of the plant growth. In view of this limitation, plant tissue S concentration is perceived to be the best test to give an accurate account of S availability to the plant. Analysis of the tissue S concentration data across the experimental sites for the two growing seasons showed a highly significant positive correlation ($r \sim 0.88$) between the S application rate and tissue S concentration, suggesting that there was an increased S concentration in the soil solution for plant uptake due to increased S fertilizer application. This is consistent with the observation of Kovar (2021). Several studies have shown that the total S concentration of plant tissue can be used as an index of sufficiency or insufficiency of S in the plant tissue (Carciochi et al. 2019; Kovar 2021). From considerable data spanning the southeastern United States, Kamprath and Jones (1986) identified a plant tissue S concentration of 0.15% as the critical level of S sufficiency in maize and reported that maize responds well to S fertilization, particularly when tissue S concentration is less than 0.15%. Similarly, Bryson and Mills (2014) reported that a tissue S concentration of 0.15% is considered adequate for maize. A similar observation was reported by Kaur et al. (2019) from a two-year field study at 10 locations in North Dakota. However, in another study, Kang and Osiname (1976) considered 0.14% S as the critical level of S concentration in maize ear leaf in Nigeria. This variation in critical limits may be due to the type of extractant, soil type, and cultivar used, among other variables. Therefore, in our study, we based the critical tissue S concentration sufficient for maize at 0.15%, below which maize productivity could be negatively affected.

Averaged across all experimental sites and for the two growing seasons, tissue S concentrations of the control and treatments with an application rate of up to 20 kg S ha^{-1} were consistently below the critical level for proper growth and development of maize. Thus, it was not surprising that the control treatment and treatments of up to 20 kg S ha^{-1} produced low yields. A modest S application rate of 30 kg S ha^{-1} significantly increased the tissue S concentration to levels considered adequate for maize productivity ($\sim 0.154\%$ and $\sim 0.171\%$, respectively, for 2018 and 2019). Increasing the S application rate resulted in further increases in tissue S concentrations; plants receiving 70 kg S ha^{-1} had the greatest tissue S concentrations. Carciochi et al. (2019) reported that application of S beyond those to achieve the critical plant tissue S concentration will cause its concentration in the plant to increase because it is not diluted by added dry matter accumulation, since it does not necessarily contribute to increasing productivity. In the present study, across all experimental sites and in the two growing seasons, an S application rate of 30 kg S ha^{-1} was identified as the minimum rate that would ensure an adequate S supply for the maize plants to truncate S deficiency limitations on maize productivity.

Economically optimum sulfur application rate

According to the Mitscherlich model, with all other limiting essential plant nutrients supplied in adequate levels, S application explained about one-half of the variation in the yield increase (R^2 ranging between 0.48 to 0.54; [Figure 3](#)). This suggests a profound effect on yield variation by other factors, such as soil characteristics, rainfall, and other weather and environmental variables. Averaged across all experimental sites, maize yield with the control (0 S) was 2.66 and 3.84 Mg ha⁻¹ in 2018 and 2019, respectively ([Figure 3](#)). The increased average yield in 2019 could be attributed to a better rainfall distribution during growing season than in 2018. This is consistent with yields reported in Kugbe, Kombat, and Atakora (2019) for trials conducted in the AEZs, in which S was omitted from balanced fertilization (minus-S treatment). Applying the limiting essential nutrients with a modest rate of 10 kg S ha⁻¹ increased maize yield by 6% and 9% for the 2018 and 2019 growing seasons, respectively. Further increases of S application to 20, 30, 40, 50, 60 and 70 kg ha⁻¹ resulted in maize yield increases of 12% and 17%, 23% and 29%, 24% and 31%, 25% and 33%, 25% and 34%, and 25% and 34%, respectively, for the 2018 and 2019 growing seasons compared to the control. Thus, across all experimental sites and in both growing seasons, the greatest yield increase occurred with an S application rate of 30 kg ha⁻¹, and the rate of yield increase leveled off at an application rate of 50 kg S ha⁻¹.

The optimal S rate derived from the response curves suggest an S fertilizer rate greater than 20 kg ha⁻¹ but lower than 50 kg ha⁻¹. Based on agro-input prices at the local level and farm-gate prices of maize for the 2018 and 2019 growing season (Esoko 2021), the calculated potential gross profits from S application at rates of 20, 30, 40, and 50 kg ha⁻¹ were GH¢ 1,850, GH¢ 2,510, GH¢ 2,220, and GH¢ 1,980 ha⁻¹, respectively, and those of the 2019 growing season were GH¢ 1,660, GH¢ 2,250, GH¢ 2,080, and GH¢ 1,790 ha⁻¹, respectively (GH¢ 1 = U.S. \$0.174). This suggests that potential profit from S fertilizer application on these S-deficient soils was maximized at an S application rate of 30 kg ha⁻¹. Thus, the resultant economically optimum S rate for both years was ~30 kg S ha⁻¹ (~43% of the highest application rate of 70 kg ha⁻¹), with a projected average maize yield of between ~4.2 and 5.3 Mg ha⁻¹, representing >90% of the observed yield with the highest S application rate. Accordingly, with all other things being equal, application of S at a rate of 30 kg ha⁻¹ will result in a GH¢ 460.00 reduction in fertilizer cost per hectare, compared to an S application rate of 70 kg S ha⁻¹, but with an insignificant reduction (GH¢ 82 ha⁻¹) in total revenue (based on farm-gate prices), ultimately resulting in fertilizer cost savings of ~GH¢ 378 ha⁻¹.

Studies have shown that economically optimum fertilizer rates are usually lower than those needed for an optimal yield because, above a certain application rate, with all other production variables being constant, the yield increase per unit of fertilizer applied decreases with an increasing fertilizer application rate, whereas the cost of fertilizer continues to be proportional to the amount applied regardless of the quantity (modified from Valkama, Uusitalo, and Turtola 2011). Thus, the economically optimum S rate cannot be a mere fixed percentage of that required for the maximum yield response, because the economically optimum rate will always depend on the price combination of S fertilizer and the marketable yield, which, more often than not, fluctuates in a free-market system (McConnell and Dillon 1997). This portends that S fertilizer application should always be economically justified for sustainable and profitable agricultural production.

Effect of sulfur application rate on sulfur and nitrogen recovery efficiency

As expected, S application resulted in significant increases in S uptake, with an increasing rate of S application resulting in corresponding increases in S uptake. Application of a modest rate of 10 kg S ha⁻¹ increased S uptake 84% and 104% for the 2018 and 2019 growing seasons, respectively, relative to the control (0 S). Further increases of the S application rate to 20, 30, 40, 50, 60

and 70 kg ha⁻¹ resulted in S uptake increases of 130% and 172%, 154% and 202%, 164% and 208%, 171% and 210%, 176% and 211%, and 176% and 213% for the 2018 and 2019 growing seasons, respectively, compared to the control. The greater S uptake values in the 2019 growing season than in 2018 could be a direct effect of the rainfall distribution that occurred during the two growing seasons. Rainfall intensity at the beginning of the 2018 growing season, when the maize seedlings had just emerged, was very high (higher amounts occurring in relatively fewer days; Figure 2) and possibly resulted in substantial S losses. Irrespective of differences in the level of S uptake during the two growing seasons, the significant increases in S uptake with an increasing S application rate suggest that more S became available in the soil solution for plant uptake when the S application rate was increased. Several studies have shown this trend of increasing S uptake resulting from increasing S application rate (Bharathi and Poongothai 2008; Mehta, Shaktawat, and Singhi 2005; Majumdar, Nagaraj, and Trivedi 2002). Carciocchi et al. (2019) reported that plant-available S generally increased with an increasing S application rate in three soils with different physicochemical characteristics and varying initial SO₄-S contents. Matamwa et al. (2018) noted that the S uptake of maize grain and stalk increased significantly with increasing S availability in the root zone. Kovar (2021) reported that application of S significantly increased total biomass S uptake with increasing S availability to the plant. Thus, the higher S uptake with a higher S application rate was not surprising.

On the other hand, apparent S recovery efficiency decreased with an increasing S application rate. This is consistent with results from the study of Adjei et al. (2000), who observed a decreasing fertilizer uptake efficiency with increasing fertilizer application rate. Several studies have shown a negative correlation between nutrient application rate and nutrient recovery efficiency, with increasing nutrient recovery efficiency as nutrient application rate decreased (Gahlout, Singh, and Lal 2010; Carciocchi et al. 2019; Kaur et al. 2019). This could be attributed to the crop's inability to utilize all applied nutrients at high application rates and, in most cases, resulted in greater nutrient losses or, to a lesser extent, accumulation of the unused nutrient in the soil. Thus, in both years, a substantial portion the S at higher rates of application (≥ 50 kg ha⁻¹) was not utilized by the crop.

Maize N uptake and apparent recovery efficiency were positively influenced by application of S, with an increasing S application rate resulting in increasing N uptake and apparent recovery efficiency. Maurya, Sharma, and Tripathi (2005) reported that N metabolism is strongly affected by the S status of the plant and that S deficiency can reduce N use efficiency. Studies have shown that, for synthesis of S-containing amino acids, an assimilatory reduction reaction of both sulfate and nitrate is necessary, and therefore, N and S uptake and assimilation are closely linked (Sutradhar, Kaiser, and Fernández 2017). Other studies have also shown that increasing availability of S progressively enhances N uptake in maize (Mehta, Shaktawat, and Singhi 2005; Carciocchi et al. 2020) and rapeseed (*Brassica napus* L.; Fismes et al. 2000).

Apparent sulfur and nitrogen losses from applied fertilizer

Despite the increasing rate of S application (0 to 70 kg ha⁻¹), with apparent S recovery efficiency ranging from 35% to 80% and 37% to 87% during the 2018 and 2019 growing season, respectively, there was no significant difference in residual soil S concentrations among the treatments in either year (Table 4). This suggests that most of the S applied at high rates that was not taken up by the plants did not accumulate in the soil; instead, it was lost from the soil, possibly through leaching and/or surface runoff. The soils at the experimental sites were coarse-textured and with low organic matter content (Table 1), therefore the propensity of S leaching from the soil was high and could account for a large portion of S losses from the soil. Apparent S balance was calculated by subtracting the sum of normalized S uptake and residual soil S content from the quantity of S applied for each treatment to estimate S loss with each treatment. The results show that,

during the 2018 and 2019 growing seasons, an average of 17% and 11%, respectively, of the S applied at 10 kg ha^{-1} could not be accounted for and was assumed lost from the field; 24% and 18%, 29% and 21%, 36% and 43%, 49% and 43%, 57% and 54%, and 62% and 58% of S from applications at rates of 20, 30, 40, 50, 60, and 70 kg ha^{-1} , respectively, could not be accounted for and was assumed lost from the soil in the 2018 and 2019 growing seasons. It is not surprising that much of the nutrient losses occurred in the 2018 growing season, because a high rainfall intensity was encountered soon after basal fertilizer application (Figure 2), resulting in higher S leaching and/or runoff losses than in the 2019 growing season. The high S losses with high rates of S application ($\geq 50 \text{ kg S ha}^{-1}$) should be of economic and environmental concern to farmers, and such high S application rates must be avoided. Contrary to apparent S losses, the highest apparent N losses occurred with the lowest S application rate and vice versa. Increasing the S application rate induced an increasing apparent N recovery efficiency, resulting in decreasing N losses from the applied N fertilizer.

Conclusions

Across all experimental sites and in both growing seasons, S application significantly increased maize yields. However, potential profit from S fertilizer application on these S-deficient soils was maximized at an S application rate of 30 kg ha^{-1} . Thus, the resultant economically optimum S rate for both years was $\sim 30 \text{ kg S ha}^{-1}$ ($\sim 60\%$ of the application rate [50 kg ha^{-1}] adopted by most farmers in the AEZs), with a projected average maize yield of between ~ 4.2 and 5.3 Mg ha^{-1} , representing $>90\%$ of the observed yield with the highest S application rate of 70 kg ha^{-1} . Thus, applying S at a rate of 30 kg ha^{-1} will result in not only a substantial reduction in fertilizer cost, compared to an S application rate of 50 kg S ha^{-1} , but also an insignificant reduction in total revenue, consequently resulting in high potential farm income. From the combined results, we conclude that, for sustainable and profitable maize production in S-deficient soils of the savanna AEZs of northern Ghana, an S fertilizer application rate of 30 kg ha^{-1} is economically justified and that high S losses from application rates $\geq 50 \text{ kg S ha}^{-1}$ should be of economic and environmental concern to farmers; therefore, such rates must be avoided. Future research should determine the economically optimal rates for other limiting essential plant nutrients to ensure profitable maize production in the savanna AEZs of northern Ghana.

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References

- Adjei, M. B., C. S. Gardner, D. Mayo, T. Seawright, and E. Jennings. 2000. Fertilizer treatment effects on forage yield and quality of tropical pasture grasses. *Proceedings of Soil and Crop Science Society of Florida* 59:32–7.
- Agyin-Birikorang, S., I. Tindjina, A. Fuseini, H. W. Dauda, R. A. Issahaku, and U. Singh. 2020. Application timing of urea supergranules for climate-resilient maize cultivars grown in northern Ghana. *Journal of Plant Nutrition* 43 (7):949–64. doi: [10.1080/01904167.2019.1702207](https://doi.org/10.1080/01904167.2019.1702207).
- Agyin-Birikorang, S., I. Tindjina, R. Adu-Gyamfi, H. W. Dauda, J. Fugice Jr., and J. Sanabria. 2022. Managing essential plant nutrients to improve maize productivity in the savanna agroecological zones of northern Ghana: The role of secondary and micronutrients. *J. Plant Nutr.* doi: [10.1080/01904167.2022.2027984](https://doi.org/10.1080/01904167.2022.2027984)
- Bharathi, C., and S. Poongothai. 2008. Direct and residual effect of sulphur on growth, nutrient uptake, yield and its use efficiency in maize and subsequent greengram. *Research Journal of Agriculture and Biological Sciences* 4: 368–72.
- Brammer, H. 1962. *Soils. In agriculture and landuse in Ghana*, ed. J.B. Wills, 88–126. London, Accra, New York: Oxford University Press.
- Bryson, G., and H. Mills. 2014. *Plant analysis handbook IV*. Athens, GA: Micro-Macro Publishing, Inc. doi: [10.13140/2.1.1693.2646](https://doi.org/10.13140/2.1.1693.2646).
- Carciochi, W. D., F. Salvagiotti, A. Pagani, N. I. Reussi Calvo, M. Eyherabide, H. R. Sainz Rozas, and I. A. Ciampitti. 2020. Nitrogen and sulfur interaction on nutrient use efficiencies and diagnostic tools in maize. *European Journal of Agronomy* 116:126045. doi: [10.1016/j.eja.2020.126045](https://doi.org/10.1016/j.eja.2020.126045).
- Carciochi, W. D., N. Wyngaard, N. I. Reussi Calvo, A. Pagani, G. A. Divito, H. E. Echeverría, and I. A. Ciampitti. 2019. Critical sulfur dilution curve and sulfur nutrition index in maize. *Agronomy Journal* 111 (1):448–56. doi: [10.2134/agronj2018.07.0467](https://doi.org/10.2134/agronj2018.07.0467).
- Dobermann, A., and K. G. Cassman. 2005. Cereal area and nitrogen use efficiency are drivers of future nitrogen fertilizer consumption. *Science in China* 48:745–58.
- Esoko. 2021. Big data: The future of sustainable agriculture in Ghana. <https://esoko.com/big-data-sustainable-agriculture/>
- Fismes, J., P. C. Vong, A. Guckert, and E. Frossard. 2000. Influence of sulfur on apparent N-use efficiency, yield and quality of oilseed rape (*Brassica napus* L.) grown on a calcareous soil. *European Journal of Agronomy* 12 (2):127–41. doi: [10.1016/S1161-0301\(99\)00052-0](https://doi.org/10.1016/S1161-0301(99)00052-0).
- Gahlout, B., R. Singh, and G. M. Lal. 2010. Effect of levels of nitrogen and sulfur on growth and yield of maize (*Zea mays* L.). *Journal of Maharashtra Agricultural University* 35:149–51.
- Garba, I. I., J. M. Jibrin, A. Y. Kamara, A. A. Adnan, and B. L. Abdulrahman. 2020. Response of maize to secondary nutrients and micronutrients in the Guinea Savanna of Nigeria. *Journal of Agronomy* 19:120–30.
- Issahaku, A., B. B. Champion, and R. Edziyie. 2016. Rainfall and temperature changes and variability in the Upper East Region of Ghana. *Earth and Space Science* 3 (8):284–94. doi: [10.1002/2016EA000161](https://doi.org/10.1002/2016EA000161).
- ISSS/ISRIC/FAO. 1998. World reference base for soil resources. World Soil Resources Report 84. Rome: FAO.
- Jones, J. B., and V. W. Case. 1990. Sampling, handling, and analyzing plant tissue samples. In *Soil testing and plant analysis. Book Series no. 3*, ed. R.L. Westerman, 389–427. Madison, WI: SSSA.
- Kamprath, E. J., U. S. Jones. 1986. Plant response to sulfur in the southeastern United States. In Vol. 27 of *Sulfur in agriculture. Agronomy monographs*, ed. M.A. Tabatabai, 323–43. Madison, WI: ASA, CSSA, and SSSA.
- Kang, B. T., and O. A. Osiname. 1976. Fertilizer sulphur and food production. *Agronomy Journal* 68 (2):333–6. doi: [10.2134/agronj1976.00021962006800020032x](https://doi.org/10.2134/agronj1976.00021962006800020032x).
- Kanton, R., P. Prasad, A. M. Mohammed, J. K. Bidzakin, E. Y. Ansoba, P. A. Asungre, S. Lamini, G. Mahama, F. Kusi, and I. Sugri. 2016. Organic and inorganic fertilizer effects on the growth and yield of maize in a dry Agro-ecology in Northern Ghana. *Journal of Crop Improvement* 30 (1):1–16. doi: [10.1080/15427528.2015.1085939](https://doi.org/10.1080/15427528.2015.1085939).
- Kaur, J., A. Chatterjee, D. Franzen, and L. Cihacek. 2019. Corn response to sulfur fertilizer in the red river valley. *Agronomy Journal* 111 (5):2378–86. doi: [10.2134/agronj2018.05.0313](https://doi.org/10.2134/agronj2018.05.0313).
- Khan, M. J., M. H. Khan, R. A. Khattak, and M. T. Jan. 2006. Response of maize to different levels of sulfur. *Communications in Soil Science and Plant Analysis* 37 (1–2):41–51. doi: [10.1080/00103620500403804](https://doi.org/10.1080/00103620500403804).
- Kovar, J. L. 2021. Maize response to sulfur fertilizer in three Iowa soils. *Communications in Soil Science and Plant Analysis* 52 (8):905–15. doi: [10.1080/00103624.2020.1869773](https://doi.org/10.1080/00103624.2020.1869773).
- Krishnamoorthy, S. K. 1989. Sulfur fertilization for yield and quality of crops. *Proceedings of the National Seminar on Sulfur in Agriculture, Held at UAS, Bangalore*.
- Kruse, C., R. Jost, M. Lipschis, B. Kopp, M. Hartmann, and R. Hell. 2007. Sulfur-enhanced defence: Effects of sulfur metabolism, nitrogen supply, and pathogen lifestyle. *Plant Biology (Stuttgart, Germany)* 9 (5):608–19.
- Kugbe, J. X., R. Kombat, and W. Atakora. 2019. Secondary and micronutrient inclusion in fertilizer formulation impact on maize growth and yield across northern Ghana. *Cogent Food & Agriculture* 5 (1):1700030. doi: [10.1080/23311932.2019.1700030](https://doi.org/10.1080/23311932.2019.1700030).

- Kumar, H., and D. S. Yadav. 2007. Effect of phosphorus and sulfur levels on growth, yield and quality of Indian mustard (*Brassica juncea*) cultivars. *Indian Journal of Agronomy* 52:154–7.
- Littell, R. C. G. A. Milliken, W. W. Stroup, and R. D. Wolfinger. 1996. *SAS system for mixed models*. Cary, NC, USA: SAS Institute.
- Majumdar, B., M. Nagaraj, and A. Trivedi. 2002. Sulfur nutrition in plants. *Journal of Hill Research* 15:63–70.
- Matamwa, W., G. Blair, C. Guppy, and I. Yunusa. 2018. Plant availability of sulfur added to finished fertilizers. *Communications in Soil Science and Plant Analysis* 49 (4):433–43. doi: [10.1080/00103624.2018.1430236](https://doi.org/10.1080/00103624.2018.1430236).
- Maurya, K. L., H. P. Sharma, and H. P. Tripathi. 2005. Effect of nitrogen and sulfur application on yield attributes, yield and net returns of winter maize (*Zea mays* L.). *Sher Singh Haryana Journal of Agronomy* 21:115–6.
- McConnell, D. J., and J. L. Dillon. 1997. Optimization of resource use levels: Response analysis. In *Farm management for Asia: A systems approach*. *FAO Farm Systems Management Series No. 13*, ed. D.J. McConnell, and J.L. Dillon, 169–88. Rome: Food and Agriculture Organization of the United Nations.
- Mehta, Y. K., M. S. Shaktawat, and S. M. Singhi. 2005. Influence of sulphur, phosphorous and farmyard manure on yield attributes and yield of maize (*Zea mays* L.) in southern Rajasthan conditions. *Indian Journal of Agronomy* 50:203–5.
- Patil, M. N., P. W. Deshmukh, R. J. Nikesar, and K. T. Naphade. 1998. Response of groundnut to sulfur and farmyard manure on Lithic Ustorthent. *PKV Research Journal* 22:13–5.
- Rausch, T., and A. Wachter. 2005. Sulfur metabolism: A versatile platform for launching defence operations. *Trends in Plant Science* 10 (10):503–9. doi: [10.1016/j.tplants.2005.08.006](https://doi.org/10.1016/j.tplants.2005.08.006).
- SAS Institute Inc. 2018. *Base SAS® 9.4 Utilities: Reference*. Cary, NC: SAS Institute Inc.
- Schabenberger, O., and J. J. Pierce. 2002. *Contemporary statistical models for the plant and soil sciences*. Boca Raton, London, New York, Washington, DC: CRC Press.
- Singh, M. V. 2001. Importance of sulfur in balanced fertilizer use in India. *Fertilizer News* 46:31–5.
- Sutar, R. K., A. M. Pujar, B. Kumar, and N. S. Hebsur. 2017. Sulphur nutrition in maize – A critical review. *International Journal of Pure & Applied Bioscience* 5 (6):1582–96. doi: [10.18782/2320-7051.6092](https://doi.org/10.18782/2320-7051.6092).
- Sutradhar, A. K., D. E. Kaiser, and F. G. Fernández. 2017. Does total nitrogen/sulfur ratio predict nitrogen or sulfur requirement for corn? *Soil Science Society of America Journal* 81 (3):564–77. doi: [10.2136/sssaj2016.10.0352](https://doi.org/10.2136/sssaj2016.10.0352).
- Valkama, E., R. Uusitalo, and E. Turtola. 2011. Yield response models to phosphorus application: A research synthesis of Finnish field trials to optimize fertilizer P use of cereals. *Nutrient Cycling in Agroecosystems* 91 (1): 1–15. doi: [10.1007/s10705-011-9434-4](https://doi.org/10.1007/s10705-011-9434-4).
- Zhao, F., and S. P. McGrath. 1994. Extractable sulphate and organic sulphur in soils and their availability to plants. *Plant and Soil* 164 (2):243–50. doi: [10.1007/BF00010076](https://doi.org/10.1007/BF00010076).