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Sulfur Nutrition of Maize in Four Regions of Malawi

Ray R. Weil* and Spider K. Mughogho

ABSTRACT

Sulfur, though widely deficient in Africa, has received little attention by soil fertility researchers. Shifts to low-S, high-analysis fertilizers, continuous cropping, and higher-yielding varieties may have increased S limitations in maize (*Zea mays* L.) production. We aimed to characterize maize S nutritional status in farmers' fields in four regions of Malawi and determine maize response to S. Four 42 to 68 km^2 study areas were delineated, two with low-elevation lacustrine soils, and two with highly weathered residual upland soils. Maize plants in 238 farmer fields were sampled for nutrient analysis at 8- to 12-leaf vegetative and tasseling growth stages. Replicated experiments were conducted in two years on a total of 20 farms to determine maize yield responses to S with and without N and/or P. Sampling areas differed significantly in maize S concentrations, S Diagnosis and Recommendation Integrated System (DRIS) indices, and N:S ratios. For earleaves, means were 1.46 g/kg S; S DRIS index, 12.2; and N:S ratio, 11.5. The ratio of N:S in the earleaf was the best predictor of maize yield response to S ($R^2 = 0.58$). Maize yields showed a N × S interaction such that there were no responses to S unless N was also supplied. With 80 kg/ha N, a significant response to S was shown by maize in all but one of 20 experiments. A response curve for S showed that 5 to 10 kg/ha of S was optimal, with mean yield responses ranging from 90 to 142 kg grain/kg S.

The decline in the fertility of agricultural soils in Africa has been well documented in recent years, with most of the attention being focused on the so-called fertilizer elements, N, P, and K (Stoorvogel et al., 1993). Sulfur is a macronutrient that is taken up by most grain crops in amounts similar to those of P, namely 10 to 30 kg/ha. However, while P has been the subject of extensive investigations throughout Africa (e.g., Buresh et al., 1997), much less is known about the S status of African soils and the response to S amendments in crop production. Deficiency of S is likely to be widespread in Africa, especially in the savanna regions, where annual burning results in losses to the atmosphere as SO_2.

Some early reports recognized the problem. Jones (1977) reported symptoms of S deficiency on maize and groundnut (*Arachis hypogaea* L.) in parts of Malawi. A few experiments in the early literature reported significant responses by maize to S, generally in the range of 12 to 20% increases in yield (e.g., Allen [1976] in western Kenya, Grant and Rowell [1976] in Zimbabwe, and Kang and Osiname [1976] in Nigeria). However, comparatively little research was conducted to investigate the S problem. For example, a review of S fertility in Tanzania found only two experiments designed to test specifically for S response, and only one report of actual crop responses to S (Shenkalwa, 1986).

There are several probable reasons why S has not received adequate attention, especially in Africa. First, low-yield shifting–subsistence agriculture has been based on exploiting the natural reserves of S, mainly

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Abbreviations: DRIS, Diagnosis and Recommendation Integrated System; TSP, triple superphosphate.

mineral S released as soil organic matter decomposes. Second, from the 1950s through the 1980s, adequate S was commonly supplied to cropland from animal manures, or, where available, from then-popular low-analysis fertilizers such as ammonium sulfate and single superphosphate. These fertilizers were applied for their N and P contents, but actually supplied more S than either N or P. In addition, certain technical issues have mitigated against research on S fertility. One was the lack of simple, inexpensive, reliable methods for analysis of plant and soil S and SO_4 (du Toit and du Preez, 1995). Another is the fact that responses to S are easily overlooked where a basal dressing of P is applied as triple superphosphate (TSP), a high-analysis fertilizer commonly assumed by researchers to be free of S (Shenkalwa, 1986). However, as reported here, TSP may contain agronomically significant quantities of S.

The situation has changed in recent years. First, as organic matter has become depleted by continuous cropping, and as higher-yielding maize hybrids are finding wider use, the supply of S from organic matter mineralization has become inadequate in many instances. Second, during the past decade there has been a rapid shift in African agriculture from the use of low-analysis fertilizers such as ammonium sulfate and single superphosphate to high-analysis fertilizers such as urea or diammonium phosphate, which contain little if any S. Where these high-analysis fertilizers are used with high-yielding maize varieties, failure to supplement with S can be expected to rapidly deplete available S supplies in the soil.

Therefore, it is not surprising that deficiency of S is becoming increasingly common in Africa on land continuously cropped for food production. For example, MacColl (1984) observed severe S deficiency symptoms on maize at the Bunda College of Agriculture Crop Production Research Farm near Lilongwe, Malawi, on land that the college had acquired from smallholder farmers. On these soils, maize gave no response to N fertilizers unless S was also added. Weil and Mughogho (1993a) reported that recycling of deep soil S was associated with higher yields of maize grown under acacia trees [*Faidherbia albida* (Delile) A. Chev] in Malawi.

The potential for increasingly widespread S limitations to crop production in Africa in general, and Malawi in particular, calls for more research to better define the extent and degree of S limitations where continuous cultivation of crops is being practiced. Our aims were to survey the S status of smallholder maize crops in Malawi and to determine the response of maize to applications of S at sites in the Balaka, Lilongwe, Mzuzu, and Salima areas.

MATERIALS AND METHODS

Four study areas of approximately 42 to 68 km^2 were delineated, two representing the low-elevation lake plain with lacustrine soils, and two at higher elevations with highly weathered residual soils (Table 1). The study consisted of two related approaches. First, a survey was conducted in which maize plants in farmer fields were sampled for nutrient analysis at two growth stages. Second, a series of five replicated on-farm experiments were conducted in two years in each of the four study areas (on a total of 20 farms) to test for maize response to added S and for interactions of N and P with S. The experimental treatments were chosen partly on the basis of a preliminary survey suggesting that maize in the study areas was commonly low in N, S, and P, but not in K or most micronutrients (Weil and Mughogho, 1993b).

The Farmer Field Survey

In each sample area, 57 to 65 farmers' maize fields were sampled, for a total of about 240 fields. Farmers' fields were included in the survey according to the following criteria:

1. The field location should contribute to as even a distribution of sample sites over the sampling area as possible.
2. The principal crop must be maize (but may be intercropped).
3. The maize stage of growth must be within certain limits at the time of the visit. For the first sample date, the plants should be in the V6 to V12 stage of vegetative growth. For the second sample date, the plants should be in the tasseling stage. (The actual stage of development ranged from silking to early milk.)
4. The field must have a uniform-appearing 10 by 10 m area for sampling (no termite mounds, ash piles, trees, or obvious changes in slope or soil color).

For each field, the farmer was interviewed to determine management practices used. All sampled fields grew local, open-pollinated maize or one of two maize hybrids. All fields were under hand-hoe ridge cultivation. The vast majority of fields had not been fertilized in the previous 5 yr. Only one field had received regular cattle manure dressings, and only 15 fields had received any fertilizer in the sampling year. Of the latter, two had received 23–21–0–4 N–P–K–S, while the other 13 had received urea, diammonium phosphate, and/or calcium ammonium nitrate. In each field to be sampled, a homogeneous-appearing area of 100 m^2 was marked for repeated sampling.

From each field, leaves from 15 to 20 maize plants were sampled on two dates: the most recently matured leaf on the early date and the earleaf (leaf blade opposite and below the ear) on the later date. No whole plants, but only leaves, were sampled, because we found that farmers objected to the removal of whole plants, and the ensuing negotiations would have greatly slowed the progress of the survey.

All sampled leaves were rinsed in distilled water and placed in cloth bags for transport to the lab, where they were dried in a forced-air oven at 70°C and ground in a stainless steel

Table 1. Selected characteristics of the four sampling areas used in the crop survey and on-farm experiments in Malawi.

Name	Maize growing season	Main soil groups	No. of fields sampled	Elevation	Rainfall	Size of area
				m	mm/yr	km^2
Balaka	Early Nov.–mid-Apr.	Ustolls, Aquepts, Fluvents	57	600–650	1000–1200	42
Salima	Mid-Nov.–mid-Apr.	Aquepts, Fluvents Psamments	57	500–550	800–1000	58
Lilongwe	Mid-Nov.–early Apr.	Ustalfs, Ustox	59	1100–1200	1100–1300	68
Mzuzu	Early Dec.–mid-Apr.	Ustox, Ustalfs, Ustults	65	1100–1300	1300–1500	68

mill to <1 mm. A subsample of ground tissue was dry-ashed in a muffle furnace at 450°C for analysis of S content by turbidimetry (Chapman and Pratt, 1961). Total N in maize tissue was determined with a LECO high-temperature combustion CHN Determinator (Leco, St. Joseph, MI). The remaining nutrient elements (including P, B, and all the metallic cations) were determined by emission spectrophotometry after digestion and dissolution in acid at the Plant and Soil Analysis Lab of the University of Georgia (Plank, 1992).

1990 Experiments

In the 1989 to 1990 growing season, we established experiments (referred to as the 1990 experiments) using a randomized complete block design with two replications on each of five farmer maize fields in each of the four study areas. Eight treatments consisted of factorial combinations of two levels of N, S, and P (with or without), with rates of application of 80, 20, and 20 kg/ha for N, S, and P (supplied as urea, gypsum, and TSP). Depending on deficiencies suspected from the results of the preliminary survey, two additional nutrients (among Mn, Cu, Zn, and Mg at 10, 6, 8, and 20 kg/ha, respectively) were applied factorially in combination with the four N $\times$ S treatments to give an additional eight combinations, for a total of 16 treatments. All fertilizers were applied as a point-placed sidedressing 5 cm deep and 10 cm away from each hill of three maize plants. Each treatment plot was 9.7 m^2. Hills were spaced 90 by 90 cm apart on ridges to give 37 000 plants/ha. Since no significant effects or interactions of Mn, Cu, Mg, or Zn were observed (with the exception of one slightly negative response to Zn at a single site), those plots effectively served as additional replication of their underlying N $\times$ S treatments in the analysis of variance.

The experiments were laid out in November 1989, and treatments were applied in December 1989 to January 1990. Plot layout, fertilizer application, soil and plant sampling, and harvest were conducted by the authors. All other aspects of crop management, including sowing and weeding, were the responsibility of the farmer cooperator. Harvest of the experiments and measurements of grain yield were completed by the end of June 1990.

Maize tissue was sampled from the experimental plots and analyzed as described for the survey, except that for the experiments, whole plants were harvested at the V6 to V12 stage. Yield of stover and grain (expressed as grain with 130 g/kg moisture) was determined by weighing the entire production of each plot in the field and bringing a five-plant subsample from each plot back to the lab to determine field moisture content.

1991 Experiments

In 1990 to 1991, we established new experiments (referred to as the 1991 experiments) in collaboration with same 20 farmers as in the previous year, but with a somewhat altered treatment structure and with three replications on each farm. The new experiments included eight treatments that were factorial combinations of two levels of N, S, and P (with or without), but this time the applied levels were 80, 20, and 50 kg/ha for N, S, and P, respectively. In addition, plots receiving N and P plus either 5, 10, or 15 kg S were included so that a S response curve could be generated with levels ranging from 0 to 20 kg/ha S.

Planting was done by collaborating farmers in December 1990, and fertilizers were applied by the authors after stand establishment was assured in January 1991. Dry matter weights and tissue samples were obtained for whole maize plants at the V12 stage about one month after fertilizer application and earleaf samples were taken at tasseling. Grain and stover yields were determined and tissue nutrient content analyzed as described for the 1990 experiments.

Calculation of Nutrient Indices

The Diagnosis and Recommendation Integrated System is a method of interpreting plant tissue analyses that was designed to be especially useful when several nutrient deficiencies are suspected (Sumner, 1979). The DRIS ranks the importance of the various nutrients in limiting plant yield and estimates the degree to which each of the limiting nutrients is deficient. The DRIS uses a system of nutrient balance indices rather than critical values or ranges for each nutrient. We calculated DRIS indices for both young maize plants and for earleaf samples using the appropriate DRIS norms and computer programs of Walworth and Sumner (1987). The DRIS norms in these programs were determined from the means and standard deviations of the ratios of various nutrients (e.g., N:K, N:P, P:K, etc.) in a large worldwide population of high-yielding maize (Walworth et al., 1986). DRIS norms are used to calculate the DRIS index for a given sample. We calculated DRIS indices using ratios for all 11 nutrients analyzed (N, P, K, S, Ca, Mg, Fe, Mn, Zn, Cu, and B).

The general expression used to calculate DRIS indices was given by Walworth and Sumner (1987) as

$$\mathrm{AI} = [+ f(\mathrm{A/B}) - f(\mathrm{C/A}) + f(\mathrm{A/D})... + f(\mathrm{A/N})]/z \quad [1]$$

where A...N are nutrients (and dry matter), AI is the DRIS index for nutrient A and when A/B $\geq$ a/b,

$$f(\mathrm{A/B}) = \{[(\mathrm{A/B})/(\mathrm{a/b})] - 1\} \times (1000/\mathrm{CV}) \quad [2]$$

or, when A/B < a/b,

$$f(\mathrm{A/B}) = \{1 - [(\mathrm{a/b})/(\mathrm{A/B})]\} \times (1000/\mathrm{CV}) \quad [3]$$

in which A/B is the observed ratio of two elements in the tissue, a/b is the norm for that ratio in a large population of high-yielding plants, CV is the coefficient of variation associated with the norm, and z is the number of functions comprising the nutrient index. A DRIS sulfur index of zero would theoretically indicate an optimal balance between S and all the other nutrients considered. A negative DRIS index indicates a relative deficiency; a positive index indicates a relative excess. The more negative the index, the more serious the deficiency.

The SYSTAT program (Wilkinson, 1990) was used to run analyses of variance on each experiment individually, and on the pooled experiments from each sampling area (with treatment, replications within farms, and sampling area as factors). SYSTAT was also used to run linear regressions and correlations between variables, and to estimate linear-plateau response equation parameters by nonlinear regression. An α level <0.05 was considered to indicate statistical significance unless otherwise stated.

RESULTS AND DISCUSSION

Farmer Field Survey

The main results from the survey regarding S levels in farmers' maize plants are shown in Table 2. There were significant differences among the four sampling areas with respect to each of the plant S parameters determined. Since with only a few exceptions, the sampled fields had not received any fertilizer for at least

Table 2. Mean S tissue concentrations, S DRIS indices and N:S ratios for young maize leaves (V6 to V12 stage) and for maize earleaves at tasseling in four study areas in Malawi, including the correlations between the two stages of growth.

Sampling area	Concentrations in dry tissue: Pearson correlation r	Concentrations: Means, Young leaf (g/kg)	Concentrations: Means, Earleaf (g/kg)	DRIS index: Pearson correlation r	DRIS index: Means, Young leaf	DRIS index: Means, Earleaf	N:S Ratio in tissue: Pearson correlation r	N:S Ratio: Means, Young leaf	N:S Ratio: Means, Earleaf
Balaka	0.41**‡	2.01Aa†	1.34Bb	0.15NS	4.6Ba	20.2Aa	0.10NS	15.3Aab	10.3Bb
Lilongwe	0.01NS	1.93Aa	1.38Bb	−0.07NS	8.4Aa	−3.4Bb	0.27NS	13.3Ac	12.6Ba
Mzuzu	0.31*	1.58Ab	1.46Bb	0.15NS	5.2Aa	5.7Ab	0.27NS	15.6Aa	12.4Ba
Salima	0.51**	1.82Aa	1.66Ba	0.40**	−5.7Bb	27.8Aa	0.22NS	14.2Abc	10.9Bb
Combined	0.22*	1.82A	1.46B	−0.02NS	3.3B	12.2A	0.15NS	14.7A	11.5B

*, ** Significant at $\alpha = 0.05$ and 0.01, respectively. NS, not significant.

† Within a column, means followed by the same lowercase letter are not significantly different according to Tukey's F-protected test at $P = 0.05$. Means within a row followed by the same uppercase letter are not significantly different according to paired t-test at $P = 0.05$.

5 yr, it is not surprising that the S content of the maize was mostly quite low. For the young maize plants, values of S in dry tissue ranged from 0.8 g/kg to 3.0 g/kg , with significantly lower mean levels in the Mzuzu area than in the other areas. This result may be related to the organic matter content (average 6 g/kg organic C) in the surface horizons of Mzuzu-area soils, which is significantly lower than that in the other areas.

As expected, S contents in earleaf tissue from plants in tassel (Table 2) were generally lower than those in the young plant leaf samples from the same fields. This trend is in agreement with the commonly reported observation that tissue content of most nutrients (Ca and Mg excepted) declines as plants mature (e.g., Andrew, 1986 and Sumner, 1979). The overall mean earleaf S concentration was 1.46 g/kg, just below the lowest of the critical values (1.5 g/kg) reported in the literature (Reuter and Robinson, 1986). The mean earleaf S concentration in the Salima area was significantly higher than in the other areas, with most of the values for the Salima area above the critical level, while the majority of samples in the Lilongwe and Balaka areas were below the critical level. Certainly, by the critical value criteria, the S content of the maize in the majority of farmers' fields in Malawi can be considered marginal to deficient. In addition, in all areas we observed symptoms of S deficiency on young maize plants more frequently than those of any other nutrient deficiency except N deficiency.

There was only a weak overall correlation between S concentration of young plant leaf tissue and that of plants in the tassel stage (Table 2). The correlation ranged from $r = 0.51$ in the Salima area to a nonsignificant $r = 0.01$ in the Lilongwe area. The correlations were highest in the two areas with sandy, less weathered soil profiles and lowest in the Lilongwe area, which has well-developed soil profiles that include red subsoil accumulations of weathered, low-activity clays. We speculate that in the latter area, plants deficient in S early in the season may have accessed sulfates adsorbed on anion exchange sites deep in the profile later in the season, while in the two lake plain areas (Balaka and Salima), the plants were more dependent on mineralization of organic S for their S supply throughout the season.

The DRIS index data was characterized by much greater variation and more extreme values (ranging from 138 to −40 for earleaf indices) than were evident in the tissue concentration data. One reason for this was that, although we observed no plant symptoms of either B or Cu deficiency, about 10% of the samples had very low values for tissue B and Cu (<0.5 mg/kg B and <2 mg/kg Cu, data not shown). These extremely low B and Cu values resulted in very high DRIS indices for most other elements, including the S DRIS index, which exceeded 100 in these cases. This apparent distortion is related to a criticism leveled at the DRIS by Baldock and Schulte (1996), in which they pointed out that because the DRIS indices are not independent, the level of one nutrient can have marked effects on the indices of other nutrients.

The S DRIS indices for young plant leaves were generally only slightly positive (mean values of 4.6 to 8.4), except in Salima, where the mean S DRIS index was −5.7, significantly lower than in the other three areas. The S DRIS indices for earleaves at tasseling were mainly positive in the lake plain areas (Balaka and Salima), where the mean S DRIS indices for earleaves (20.2 and 27.8, respectively) were significantly higher than in the Lilongwe and Mzuzu areas (−3.4 and 5.7, respectively), and much higher than the corresponding young plant S DRIS indices. The S DRIS indices in the Lilongwe and Mzuzu areas did not appear to change much between the two stages of growth. There was little relationship between the young plant and earleaf DRIS indices (Table 2), except in Salima, where there was a weak but significant correlation $r = 0.40$) between the two.

Since a major physiological function of S is the formation of proteins that contain both N and S, the ratio of N:S in plant tissue is commonly used as a measure of S nutritional status of plants, with an N:S ratio >12 often cited as indicative of S deficiency in maize. The N:S ratio in the surveyed maize plants varied from 5 to 26 (data not shown). The vast majority of young maize plants in all four areas had N:S ratios greater than the critical value, but plants in Mzuzu had a mean N:S ratio significantly higher than the other areas (Table 2). The overall mean N:S ratio was higher in the young plant leaves (14.7) than in the earleaves (11.5). The lake plain areas had significantly lower N:S ratios in the earleaves than did Lilongwe and Mzuzu, where in about half the

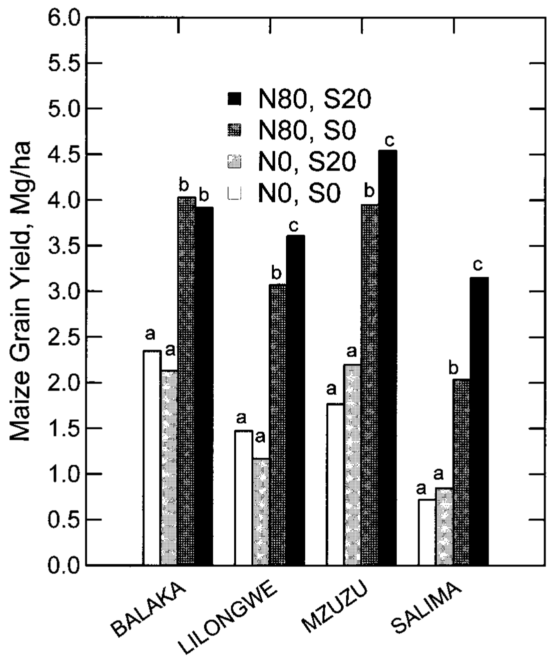

Fig. 1. Effect of N and S fertilizer on maize grain yields in on-farm experiments in four areas of Malawi in 1990. Plots received N at either 0 or 80 kg/ha and S at either 0 or 20 kg/ha.

cases the N:S ratio exceeded 12 in the earleaves. In none of the areas was the N:S ratio in young plant leaves significantly correlated with that in the earleaves (Table 2). In general, the S status of young maize plants in a field (whether indicated by tissue S, S DRIS index, or N:S ratio) was a very poor predictor of the S status of maize later in the season (tassel stage) in the same field.

1990 Experiments

Of the 20 experiments (40 total replications) established in 1990, yield data were successfully obtained from only 14.5 (29 replications), because of losses prior to grain harvest due to termites, drought, wayward cattle, thieves, or premature harvest by the farmer cooperator. The data within each of the four sampling areas (five to nine replications) was pooled for analysis of variance. The data shown in Fig. 1 are averages across treatments with and without P application (there were no interactions with P, and P had relatively little effect on yields, giving a significant increase in only one of the experiments). Yields of unfertilized maize (mainly open-pollinated land races) were highly variable, ranging from a low of 134 kg/ha in one plot in Balaka to 5809 kg/ha in the highest plot in Mzuzu (data not shown). Mean yields of unfertilized maize for the four areas (Fig. 1) ranged from 691 kg/ha in Salima to 2158 in Balaka, very close to the range reported by other surveys of on-farm yields in Malawi (Malawi Government, 1977, p. 19–46; Weil, 1985). The response to N, with or without S, was significant in all four areas (and on all but one individual farm), the average response to 80 kg N/ha ranging from 1300 kg/ha of maize grain in Salima to 2150 kg/ha in Mzuzu (Fig. 1). The N responses were thus in the range of 16 to 27 kg grain/kg N applied, very similar to the 11 to 23 kg grain/kg N reported by others in Malawi (Saka et al., 1992) for the first 60 kg N applied. The similarity of the unfertilized maize yields and N responses in our study to those in other reports suggests that our set of on-farm experiments succeeded in sampling typical Malawi smallholder conditions.

The analysis of variance showed a significant N $\times$ S interaction, such that the effect of S was generally significant only when N was also applied. Conversely, we observed that the addition of N without S exacerbated S deficiency symptoms (stunting and interveinal chlorosis on younger leaves) in several of the experiments, although the practice never significantly decreased grain yields. When 80 kg N/ha was applied, the application of 20 kg S/ha gave a significant increase in maize yield in all the Lilongwe, Mzuzu, and Salima experiments, but in only one experiment in Balaka. In Salima, where the responses to S were greatest, 1 kg of S produced an average increase of 55 kg of maize grain (1100 kg increase from 20 kg of applied S). The potential response per kilogram of applied S may have been as much as four times greater than this, since, as discussed below, the following year's experiments indicated that the same response probably could have been obtained with only 5 kg of S.

1991 Experiments

A second series of 20 on-farm field experiments was conducted in 1991. Yields with no N applied averaged 1121 kg grain/ha, similar to the results of the 1990 experiments. On all farms but one, maize responded significantly to the application of 80 kg N/ha, whether or not other nutrients were also applied. However, there was a significant N $\times$ S interaction in all four areas such that the effectiveness of N fertilizer was enhanced when accompanied by application of S fertilizer (Fig. 2). Responses to 80 kg N/ha ranged from 1530 kg/ha maize in Mzuzu to 2900 kg/ha maize in Salima with no S applied, but from 2600 to 3960 kg/ha maize when 20 kg/ha S was applied.

There was no response to S without N application, but when 80 kg N/ha was applied, the application of 20 kg S/ha increased maize yields from an average of 490 kg/ha (13% increase) in Lilongwe to 940 kg/ha (34% increase) in Mzuzu. These results, shown in Fig. 2, are means averaged across plots with and without applied P.

Figure 3 shows the mean effects of S and P application on maize yields for each area when 80 kg N/ha were applied. Just as S deficiency symptoms were observed more often than P deficiency symptoms in the 1990 survey, the maize response due to S in 1991 was more frequently significant and generally larger than that due to P. In the two lake plain areas (Balaka and Salima), P did not give any increase in maize yield, either where S and N were adequate (Fig. 3) or where P was applied alone (data not shown). In the upland areas of highly weathered soils (Lilongwe and Mzuzu), application of 50 kg/ha P along with 80 kg/ha N and 20 kg/ha S did give significant responses, and of somewhat greater magnitude than those due to S. Results for P application

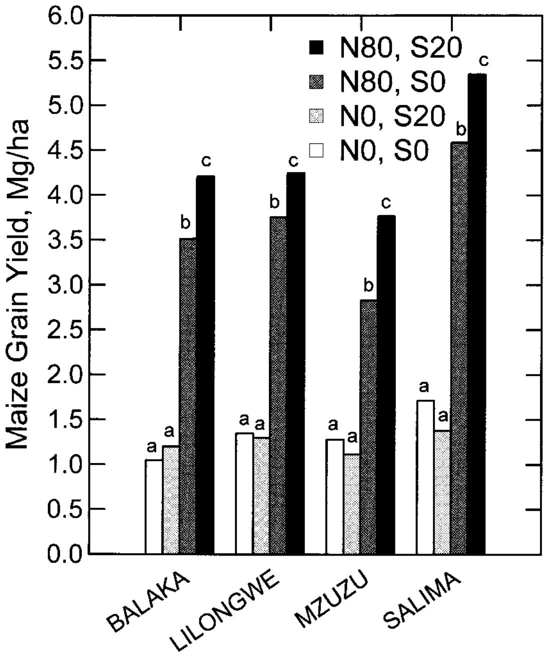

Fig. 2. Effect of N and S fertilizer on maize grain yields in on-farm experiments in four areas of Malawi in 1991. Plots received N at either 0 or 80 kg/ha and S at either 0 or 20 kg/ha. Within an area, bars labeled with different letters indicate a significant treatment difference at *P* = 0.05.

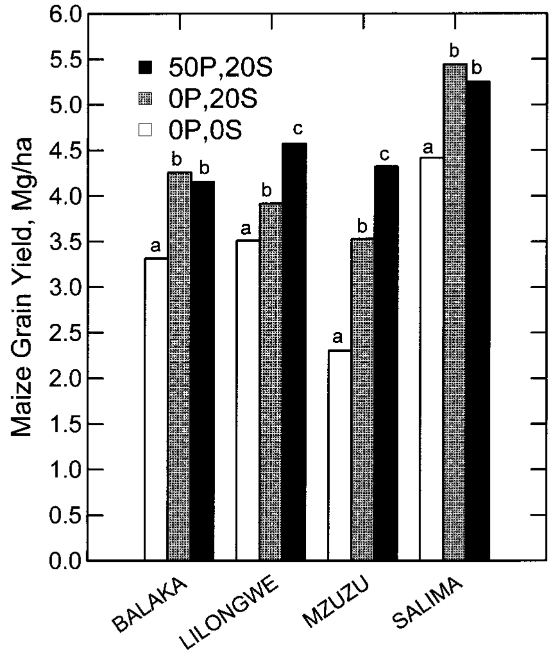

Fig. 3. Effect of S and P fertilizer on maize grain yields with adequate N fertilization in on-farm experiments in four areas of Malawi in 1991. All plots received 80 kg N/ha. Sulfur was applied at 0 or 20 kg/ha and P at 0 or 50 kg/ha. Within an area, bars labeled with different letters indicate a significant treatment difference at *P* = 0.05.

without S are not shown in Fig. 3 because of the potentially confounding S content of the P source used (discussed below).

Because responses to S were widespread in the 1990 experiments, and S deficiency symptoms were widely observed in the 1990 survey, we added several levels of S to the 1991 experiments to enable the generation of S response curves. Figure 4 shows the average response in each area to S applications from 0 to 20 kg S/ha (50 kg P/ha and 80 kg N/ha were applied at all S levels). Linear-plateau response models shown in Fig. 4 indicate that 5 to 6 kg S/ha was generally sufficient for optimal maize grain yields under these conditions. The predicted response to these levels of S ranged from 450 kg/ha (90 kg maize/kg S) in Salima to 850 kg/ha (142 kg maize/kg S) in Mzuzu.

Our results agree with other reports of S responses in Africa. Friessen (1991) measured grain yield responses to S in 20 site-years in subhumid and semiarid areas of West Africa and found a similar magnitude of responses (200 to 2000 kg/ha) and a similar optimal S rate (5 to 10 kg/ha). Earlier work in Zimbabwe by Grant and Rowell (1976, 1978) concluded that S uptake was dependent on site and variety grown, but averaged 10 kg S/ha when maize grain yields averaged 7000 kg/ha. Our results are also in agreement with those of Kang and Osiname (1976) in Nigeria, who reported that at all six sites where their experiments were conducted, maize yield response to S was significant only for the first 7.5 kg/ha of S applied. Ojeniyi and Kayode (1993), using rates of S fertilizer ranging from 10 to 80 kg S/ha, found no responses from rates higher than 10 kg S/ha, and reported that only this rate increased maize yields in the year following the application year. Kayode (1990) also reported that 10 kg S/ha was adequate for cowpea [*Vigna unguiculata* (L.) Walp.] production in both the rain forest and the savanna zones of Nigeria. Later he observed that higher rates had little effect on yields, or in some cases actually depressed yields (Kayode and Ojeniyi, 1991). Bromfield et al. (1981) used phosphate rock and added either 21 or 64 kg/ha of elemental S. Although they did not differentiate between the effects of S as an acidifying agent for the phosphate rock and as a nutrient, they observed that the added S improved maize yields only in the first season after application, and that there was no additional benefit from the higher rate of S.

The true response to S in our study may have differed somewhat from than the 450 to 850 kg maize/ha reported above, since all treatments making up the S response curve received 50 kg P/ha as triple superphosphate. After the experiment was completed, we analyzed the TSP used (which was of Norwegian origin), as well as three other TSP samples from the USA and Kenya, and found that both materials contained 25 to 31 g/kg total S. Therefore, the basal dressings of TSP probably alleviated some S deficiency in even the zero-S plots, since the TSP used to supply 50 kg P would have also supplied approximately 6 kg S. Thus, the yield plateau may be more accurately characterized as occurring at an S application level of 10 to 12 kg/ha. Since the true yield response to S would also be somewhat greater, we cannot calculate exactly what the response per kilogram S applied would have been had we used a P source that did not contain any S. The fact that many workers in soil fertility have not recognized the 20 to 30 g/kg S content

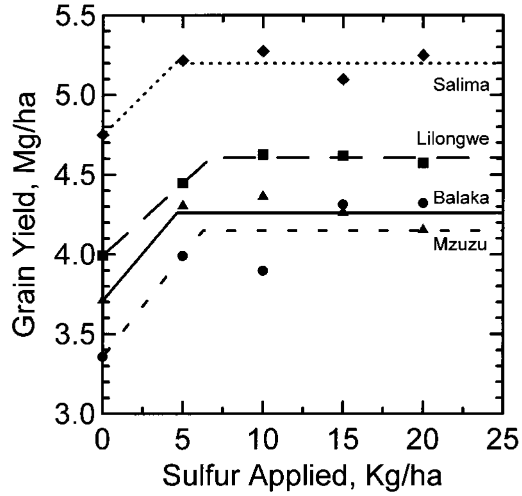

Fig. 4. Response of maize to S applied as gypsum in 20 on-farm experiments in four areas of Malawi. All plots received adequate N and P. The lines represent best-fit linear-plateau models of the form $y = (a + bx) \times (x < \text{SUFF}) + (c \times \text{SUFF}^2) \times (x \geq \text{SUFF})$, where SUFF is the value of *x* at which *y* reaches the plateau, and *a*, *b*, and *c* are regression-estimated parameters. Corrected R^2 values were 0.90, 0.99, 0.92, and 0.81 for Salima (diamonds), Lilongwe (squares), Balaka (circles), and Mzuzu (triangles).

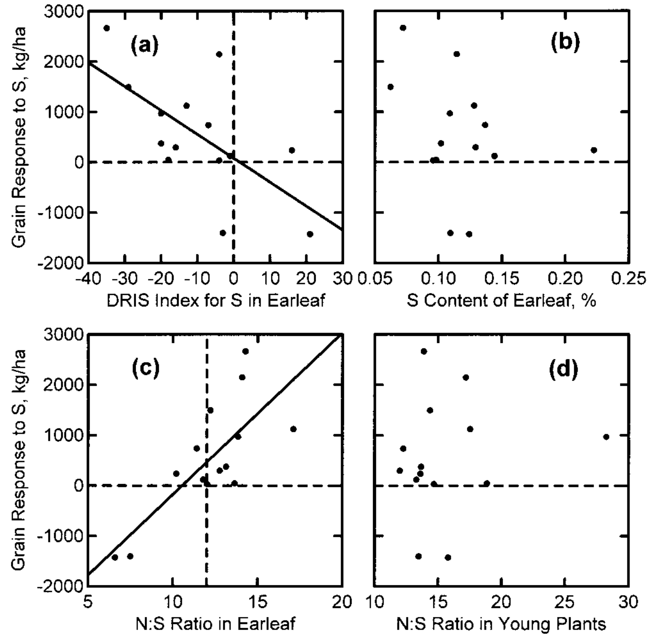

Fig. 5. The utility of four tissue S parameters in predicating maize grain yield response to S application in 14 on-farm experiments in Malawi in 1990. The dashed vertical line at DRIS index = 0 indicates where S is theoretically perfectly balanced with all other nutrients and the point beyond which no positive response to S would be expected. The dashed vertical line at N:S ratio = 12 indicates an often-cited value for the maximum ratio for S sufficiency. (*a*) Resp = 75.8 − 47.5(DRIS), R^2 = 0.41*; (*c*) Resp = −384 + 320(N:S ratio), R^2 = 0.58. *, ** Significant at the 0.05 and 0.01 probability levels, respectively.**

of TSP suggests that crop responses ascribed to P application in many reports may actually have been due partly to S.

Based on the present results and those of other studies, it would seem that 5 to 10 kg S/ha is generally sufficient for maximum response by maize at yield levels <6 mg/ha. The size of the responses observed in our study would suggest that supplementing N fertilizers with S, perhaps by developing local sources of gypsum or elemental S, has the potential to be a very economical way of boosting maize production among those smallholder farmers who have access to moderate levels of N fertilizers. Given the low S-supplying capacity of the soils in this study, and the limited reports cited from the literature, we also speculate that S application should be experimented with for leguminous crops. However, in the absence of adequate levels of N (from either legumes, manure, or fertilizer), investments in S application would probably not be profitable.

In the low-fertilizer-input peasant agriculture typical of much of Africa, crop surveys using tissue analysis may be useful in delineating areas of particular nutrient deficiencies (Weil et al., 1991). One of the reasons for conducting the 1990 survey of maize in farmer fields was to test the hypothesis that the results of a crop tissue survey could be useful in predicting whether and to what degree maize would be likely to respond to S in a given area. Figure 5 shows the relationship between several measures of maize tissue S status on N-fertilized plots and the subsequent yield responses measured in the on-farm experiments. The earleaf S content by itself was not significantly related to yield responses to S. However, the S DRIS index did show a significant relationship (R^2 = 0.41) with yield response. As would be expected, the relationship between earleaf S DRIS index and yield response was negative, a negative DRIS index being indicative of a deficiency, which would likely result in a positive yield response. Interestingly, the regression line passes almost exactly through the origin, as would be predicted by the theory that a plant with an S index of 0 would be in balance and not show a response to added S.

The ratio of N:S in the earleaf was an even better predictor of maize yield response (R^2 = 0.58) than the S DRIS index. Yield responded positively to S application where the N:S ratio in the earleaf exceeded 10 (only slightly lower than the critical value of N:S = 12 cited earlier). In two experiments where earleaf N:S was very low (<8), application of S resulted in a yield depression. The N:S ratio in the young maize plants, however, was not significantly related to maize grain yield responses (Fig. 5). Data available on soil S in our study (not shown) was too limited to test for useful correlations, partly because of difficulties in getting repeatable laboratory results for soil SO_4–S in iron-rich, highly weathered soils (du Toit and du Preez, 1995), and partly because soil sampling to a greater depth than is practical in a rapid survey would be required to account for SO_4–S potentially available to maize.

CONCLUSIONS

The ratio of N:S in maize earleaves at tasseling was significantly related to the yield response to applied S observed in on-farm experiments. Furthermore, in the survey of maize in farmer fields, S content in leaves of young plants was not well correlated with that in earleaves at tasseling. We therefore recommend that future crop surveys aimed at delineating S deficiencies concentrate on sampling only plants near the tasseling stage of growth, and that N be analyzed as well as S so that the N:S ratio can be used to help characterize the S nutritional status of the crops in a geographic area. In our study, the DRIS index for earleaves also predicted yield response, but not as well as the N:S ratio.

Deficiency of S in farmer maize crops appears to be widespread in four areas of Malawi with greatly differing types of soils. A significant response to S was shown by maize on all but one of 20 farmer fields in which replicated experiments were conducted. Although some unintended S applied in TSP used for P application precluded exact calculations, our results suggest that the response to applied S in Malawi is likely to be between 80 and 160 kg of grain per kilogram of S applied, a rate of return that should make the use of S economically attractive in most instances. Optimal response to S was obtained with the application 5 to 6 kg S/ha in our experiments. Also, significant S $\times$ P interactions found in several of the 1991 experiments indicated that S response was reduced where TSP was applied and that P response was reduced where S was applied. These results, and our analysis of 25 to 31 g/kg S in TSP samples, suggest that care should be taken in future S and P response experiments to avoid S-containing TSP as a P source. Some responses to TSP in the literature should probably be reinterpreted, in that they may actually be partly due to the S rather than the P in this fertilizer material.

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