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Estimation of Optimum Rate of Sulfur for Application in Soils for Wheat Production in Ethiopia –III

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Authors' contributions

This was a joint work between all authors. Author AM designed the study, performed field-experiments, managed Lab analysis and wrote first draft of the manuscript. Authors TM and JMRS monitored field works, edited data, reviewed and edited the manuscript. Author NA reviewed and edited the manuscript and managed literature searches. All authors read and approved final manuscript.

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ABSTRACT

Six on-farm experiments were conducted in 2013/2014 seasons, in the Central Highlands (CHLs) of Ethiopia, with the main aim of estimating optimum sulfur rate for wheat. The treatments were, 4-levels of S(S_0 =0, S_1 =5, S_2 =10, and S_3 =20 kg S/ha); 2-levels of N(N_0 =0, N =N_1 =69 kg N/ha); and 2-levels of P(P_0 =0, P =P_1 =20 kg P/ha), supplied by gypsum, urea and triple super phosphate(TSP), respectively. The experimental design was RCBD, and the treatments were replicated three times. The grain and total above ground biomass (TAGB) yields, and number of

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tillers per plant (NTsPP) showed significant response (P<0.001) with applying S and NP. Four of the study sites: G/Silingo, Keteba, N/Suba and Bekejo showed significant response to applied fertilizers, especially S at all levels, whereas W/Gora and B/Tokofa showed marginal response, which suggested that, responses to S were varied over sites/soils. Considering the critical, soil SO_4-S, estimated from the first set of (18 S response) experiments, 11.30 mg/kg, the sites like Keteba, Bekejo and N/Suba could be rated as very low; G/Silingo medium/marginal; whereas W/Gora and B/Tokofa could be rated adequate for SO_4-S(sulfur). Based on this, therefore, site/soil specific S recommendations were made. In this respect, in Keteba, Bekejo and N/Suba sites with very low initial soil SO_4-S values, the optimum S rate can be >20 kg/ha. But, for the moment, it is advisable to apply 20 kg S/ha with the recommended doses of NP. At G/Silingo site, whose soils tested marginal for the SO_4-S, applying S at a rate of 20 kg/ha or even slightly <20 kg/ka is advisable. Whereas, at W/Gora and B/Tokofa, since the initial soils tested adequate for SO_4-S, but wheat responded to S at lower levels, applying S at a rate of 5-10 kg/ha is reasonable. In general, since in all the studied sites, the maximum attainable yield of wheat grain reported by different workers was not achieved, it is important to make further investigations to identify other limiting nutrients/factors.

Keywords: Wheat cultivar; sulfur deficiency; optimum sulfur rate; gypsum and triple super phosphate (TSP).

1. INTRODUCTION

Wheat (*Triticum aestivum* L.) is a major cereal produced in Ethiopia, widely adopted to diverse agro-ecological zones (AEZs) and soil conditions, ranging from <1500 to 3200 m above sea level. Given this wider adaptation, if major resource base, the soil together with its water resources, is preserved from degradation, undoubtedly wheat can power the intended green revolution in Ethiopia. However, in over 350 farms and households surveyed in Arsi, E/Shewa, and O/Liyuu zones, under low external input and poor management, farmers hardly obtain wheat grain yield >1.0 t/ha. This is mainly due to the declining soil fertility, because of continuous cultivation without replenishment. In the study areas, the farmers also use free grazing on farm-fields after crop harvest until next season's land preparations, which actually mine nutrients from outfields and bring to areas directly around villages/homesteads, because cattle are kept overnight at homesteads. The farm yard manure (FYM), the potential source of nitrogen(N), phosphorous(P), potassium(K) and sulfur(S) etc, is used as fuel or, if composted used only for fertilization around homestead and/or infields. This will adversely affect the nutrient balance, and hence next season's crop yields. [1], reported that, soil nutrient depletion under smallholder farming is a root cause for declining per capital food production in sub-Saharan Africa (SSA).

However, the quantity of nutrients removed by crops is a good index of fertilizer needs, and hence fertilizer addition to soils must be calculated to replace all kinds of losses. Moreover, the significance of nutrients like S, shouldn't be weighed in terms of only the quantity of produce, but also on its nutritional quality. Sulfur (S) is now recognized as the fourth major element in balanced nutrition next to NPK, and the most limiting element in wheat production, second only to N [2]. It is best known for its role in the synthesis of proteins, oils, vitamins and flavored compounds. The amino acids, methionine (21% S), cysteine (26% S), and cystine (27% S) contain S, which are the building blocks of proteins and impact quality of human food and feeds [3]. They reported that, about 90% of sulfur is present in these amino acids, and without adequate S, crops cannot reach their full potential in terms of yield/quality; nor can they efficiently use applied N. Although S is an essential macro-nutrient, the deficiency of which reduces its yield and quality [4], wheat requires only modest amount for optimum growth: e.g. 15-35 kg/ha reported by [5,6].

From this, it is clear that protein rich cereals like wheat are likely to suffer from hidden S deficiency. From the 18 first-set and 6 second-set of on-farm experiments conducted in 2012 to 2014, in a wide AEZs and soil types, it was found out that, over 60-70% of sites showed either full or marginal response to applied S [7]. It is evident that fertilizer requirements of crop plants should be on the basis of soil-test and/or crop responses. The objective of this study was therefore, 1) to further evaluate the responses of wheat to applied S and NP, and 2) to estimate optimum S rate for wheat in the study areas. The research questions intended by this set of experiment are: a) Does the application of S increase yield and yield components of wheat, and if so, b) What is optimum application rate?

2. MATERIALS AND METHODS

2.1 Description of the Study Areas

24 field experiments were conducted in 2012/2013 and 2013/2014 cropping seasons in CHLs of Ethiopia, representing major wheat growing districts in Arsi, E/Shewa and O/Liyuu administrative zones, covering different AEZs/soil types. During the first season, 18 explorative sulfur response, (first set of experiments), were executed in 18 farmers' fields, six in each zone/study area.

Six on-farm (second set of) experiments were conducted in 2013 to 2014 seasons in CHLs of Ethiopia, representing major wheat growing the same districts in Arsi, E/Shewa and O/Liyuu zones/areas, covering different AEZs and soil types to determine an optimum S rate for wheat. In the study, three study sites, namely G/Silingo, Keteba and N/Suba were selected based on 2012/2013 (last season's) 18 explorative sulfur response trials on wheat (highly responsive to applied S and NP). The sites were also found to be very low in SO_4-S, based on pre-soil tests within the season. Whereas, W/Gora, Bekejo and B/Tokofa were randomly selected without pre-soil testing, but on areas miles away from last season's sulfur responsive sites (Dosha, Bekejo and B/Tokofa respectively) to further evaluate, wheat response to sulfur.

In Arsi zone, nitosols dominate, but a considerable proportion of vertisols also exist. The upper soil layer consists of tephritic materials, whereas the substratum consists of calcareous material enriched through secondary precipitation over the bedrock. Whereas, in E/Shewa (Debre Zeit areas), dominant soil types are vertisols, and the soils are mostly calcareous, enriched with fragments of $CaCO_3$. In O/Liyuu zone (Welmera district), major soil types are nitosols and vertisols. In each administrative zone/area two sites/farmers fields were selected, and geo-referenced using Global Positioning System (GPS), assisted by Google earth (2011) and were classified by elevation, size and soil type. The GARMIN, model number GPS-60, made in USA in 2007 was used. These sites were characterized and used for conducting S response and its rate in wheat. The specific locations and salient features of selected field/sites are presented in Table 1.

2.2 Experimental Treatments and Design

A wheat cultivar, known as "Kekeba" was used as a test crop. The treatments used were, 4-levels of Sulfur(S_0 =0, S_1 =5, S_2 =10 and S_3 =20 kg S/ha); 2-levels of Nitrogen(N_0 = 0, N_1 =N =69 kg N/ha); and 2-levels of Phosphorous(P_0 =0, P_1 =P =20 kg P/ha) supplied as gypsum, urea and triple super phosphate (TSP), respectively. The nitrogen and phosphorous were applied as a recommended dose of NP for wheat production in the study areas. Randomized complete block (RCBD) was used as experimental design, and treatments were replicated three times. Each replication was sub-divided into, 3 x 5 =15 m^2 plots and there were 9-experimental units per block. One-third of N was incorporated into soils within rows at planting, whereas the remaining 2/3 was top-dressed at tillering. The entire sources of S and P were drilled within rows and incorporated into soils before seeding. The agronomic spacing for wheat, 25 cm (rows) x 5 cm (plants) was used. There were 12-rows per plot of which two were borders and one used for plant sampling. The remaining middle rows were used for yield data and seed sampling. During the crop's growing stage or before/after harvest, agronomic parameters such as number of tillers per plant (NTsPP), plant height (PH), spike length (SL), spike weight (SW), total above ground biomass dry matter yield (TAGB), grain and stover yields and number of seeds per spike (NSsPS) were recorded.

2.3 Soil Sampling and Analysis

Before planting, composite soil samples representing each block from 10-spots, (0-20cm) depth were sampled and composited together for analysis. Then, the soils were air-dried immediately in drying rooms to avoid sulfate formation from OM in transit. The dried soils were ground and sieved <2 mm and analyzed for pH, organic carbon (OC), electrical conductivity (EC), total nitrogen (TN), available phosphorous (PO_4-P), available sulfur (SO_4-S), exchangeable bases (Na^+, K^+, Ca^{2+} and Mg^{2+}), cation exchange capacity (CEC), base saturation (PBS) and texture. Some micro-nutrients like zinc (Zn) were also analyzed (data not shown). The soil physico-chemical variables were analyzed using wet-soil chemistry laboratory (Lab) at the Sokoine University of Agriculture (SUA), Tanzania using the procedures outlined in Table 2.

2.4 Data Analysis

The analysis of variance (ANOVA) was performed to evaluate treatments effects on yield and its components. Similarly, PROC-UNIVARIATE procedure in SAS [16] was used to test the normality assumptions of variables, besides analyzing residual distribution. Variance analysis was done using PROC-MIXED procedure included in SAS programme to evaluate differences between treatments. The SAS linear model statement for RCBD considers replications and treatments as fixed effects. When treatment differences were significant, least significant difference (LSD), was performed to separate means at 0.1%, 1% and 5% significant levels. Some variables like yield or its components were evaluated by correlation/regression and slopes were compared through parallelism and coincidence test using PROC-REG procedure. Moreover, pre-planned pair-wise orthogonal comparisons among treatments (SAS contrast) were performed to see significances of treatments at each level and to see effects of sulfur impurity from TSP on yield.

3 RESULTS AND DISCUSSION

3.1 Some of the Soils Physico-chemical Properties of Study Sites before Planting

Tables 3a and 3b present some physico-chemical properties of soils of the study sites before planting, and/or after sulfur treatment application. In it, a range of soil pH is presented, from acidic in O/Liyuu zone; followed by pH near neutral in Arsi; to high pH (calcareous soils, enriched with fragments of $CaCO_3$) in E/Shewa zone (Keteba and partly Bekejo sites). The calcium orthophosphate $\{Ca(H_2PO_4)_2\}$ extractable sulfate sulfur (SO_4-S) of soils ranged from, 4.03-35.83 mg/kg. Based on the 10-13 mg/kg $CaCl_2$ extractable SO_4^{-2}-S as a critical limit of S deficiency for most crop species reported by [17], therefore, 50% of the studied sites were found to be S limiting, whereas one was marginal (16.7%). But, two sites, W/Gora and B/Tokofa (33.3% of the sites) were found to be adequate for available sulfur (Table 3a).

Table 1. Geographic locations of the selected study fields/sites

Site/farmer field	Long. (E)			Lat. (N)			Elev (m).a.s.l	Soil type
	Deg(°)	Min(′)	Sec(″)	Deg(°)	Min(′)	Sec(″)		
Wonji Gora,(WG)	39	8	52.548	7	59	56.652	2239.981296	Heavy black clays, Pellic Vertisols
Gora Silingo (G/Silingo),(GS)	39	8	26.664	8	0	50.004	2150.818152	Light red clays, Nitosols
Keteba,(Ke)	39	2	20.652	8	52	48.828	2195.760912	Heavy black clays, Pellic Vertisols
Bekejo,(Bk)	38	55	47.748	8	37	22.656	1855.936344	Light black clays, Chromic Vertisols
Nano Suba (N/Suba),(NS)	38	29	59.352	8	57	14.94	2234.933808	Deep red clays, Nitosols
Berfeta Tokofa, (B/Tokofa),(BT)	38	30	49.572	9	0	13.644	2244.065616	Heavy black clays, Pellic Vertisols

Key: (°) =degree; (′) =Minute; (″) =Second decimal; Elev(m) =Altitude above sea level

Table 2. Extraction methods of selected soil variables of the study areas

Parameters	Unit	Extraction/Analytical methods by	References
pH	pH(1:2.5), soil:H_2O	Potentiometrically,1:2.5 soil:water	[8]
EC	mS/cm	1:5 soil:water suspension	[9]
Exch. bases (Ca^{++}, Mg^{++}, K^+, and Na^+)	Cmol(+)/kg	1 *M* NH4OAc solution at pH =7.00	[8]
CEC	Cmol(+)/kg	1 *M* NH4OAc solution at pH =7.00	[8]
PBS	%	Calculation from exch. bases	[8]
TN	%	Kjeldlehl as described in	[10]
OC	%	Walkley-Black as described in	[11]
Av. P	mg/kg	Bray 1; and Olsen	[12]; and [13]
SO_4-S	mg/kg	Calcium-orthophosphate, Turbidimetric	[14]
Soil texture	%(sand, silt & clay)	Hydrometer method	[15]

Table 3a. Selected properties of soils of the study areas cultivated for wheat before planting

Study Area (Zone)	District	Farmer field	Soil type	pH(1:2.5), Soil: H_2O	EC(mS/cm)	Exchangeable Bases (Cmol(+)/kg)				CEC (Cmol(+)/kg)	PBS (%)	TN (%)	OC (%)	P (mg/kg)	SO_4-S (mg/kg)	Soil Texture
						Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}							
Ar	Ti	WG	PV	6.36	0.08	15.11	4.92	0.67	2.19	32.6	70.22	0.21	2.71	2.01	31.98	C
Ar	Ti	GS	Ni	6.24	0.11	8.79	4.20	0.34	4.14	26.8	65.24	0.17	2.18	3.01	12.11	CL
ES	Ad	Ke	PV	8	0.2	30.35	8.29	0.32	3.77	45.8	93.31	0.05	1.15	9.02	6.77	C
ES	Ad	Bk	CV	7.15	0.1	19.72	5.22	0.34	2.50	33.4	83.19	0.08	1.17	12.01	4.03	SC
OL	We	NS	Ni	5.85	0.07	4.01	1.27	0.24	2.09	13.8	55.16	0.14	0.96	0.89	4.58	C
OL	We	BT	PV	4.85	0.21	7.73	2.89	0.44	2.50	36.2	37.45	0.15	2.03	0.50	35.83	C

Key: Study Areas[(Ar =Arsi, ES =E/Shewa =East Shewa, OL =O/Liyuu=Oromia Liyuu)]; Districts[(Ti =Tiyo, Ad =Ada'a, and We =Welmera)]; Farmer fields[(WG =W/Gora =Wonji Gora, GS =G/Silingo =Gora Silingo, Ke =Keteba, Bk =Bekejo, NS =N/Suba =Nano Suba, BT =B/Tokofa =Befeta Tokofa,); Soil Types[(CV =Chromic Vertisol, Ni =Nitisol, PV =Pellic Vertisol)]; and Soil Texture(C =Clay, SC =Sandy clay, and CL =Clay loam). Av P(for pH >7.0, Olsen; and for pH <7.0, Bray-1 method). The soils were classified as vertisols (Keteba, Bekejo, B/Tokofa, W/Gora) and nitosols (N/Suba and G/Silingo)

The total nitrogen (TN) content, which is ranging from 0.05-0.21%, falls within a range considered very low to low, based on the criteria developed by [18] for tropical soils.

The available Olsen P(Av. P) content for E/Shewa zone, ranged between 9.02-12.01 mg/kg, falls within a range considered to be low to marginal based on the criteria developed by [19]. Similarly, for the soils from Arsi and O/Liyuu zones, Bray-1 P, which ranged from 0.50-3.01 mg/kg, were very low based on the criterion developed by [19]. According to [20], in such low phosphorous soils fertilizer responses are most likely expected.

The organic carbon (OC) contents of soils, ranged from 0.96%-2.71%, falls in a range considered very low to low/marginal based on the criteria developed by [18]. Most importantly, the OC of most studied soils were far below the critical threshold, 2%, suggested by various workers e.g. [21], for sustaining soil health/quality, below which soils structural stability will suffer a significant decline. It is well recognized that, OC is key to sustainable agriculture, contributes significantly to C, S, and NPK and other essential nutrients, and soil functions. The OC content of soils in equilibrium with vegetation is a function of annual additions and decomposition of OM. As a result, under low external input farming, nutrients status of soils will deplete, and any agronomic practice that has impact on OM can bring changes in soil fertility, particularly OC and NPK and S. For example, according to [22] up to 98% of the total soil sulfur may be present as organic S compounds and is associated with heterogeneous mixture of plant residues, animals and soil microorganisms. In addition, the profile of organic S reported generally to follow, the pattern of OM content in soils with depth [23].

From plant and soil survey study conducted in about 350 farms/farm households in the first season (personal observation from unpublished data from the second set of experiments), it was observed that, in all the studied areas even during crops growing periods, there is continuous removal of plant biomass in the form of weed/feed and through defoliation of plant leaves, which could reduce OM return to soils that could possibly affect soil's nutrient and eco-system dynamics. Such practices in Ethiopia are especially common in the fields of cereals like maize, Tef, wheat, sorghum and finger millet. Therefore, it is not surprising that, the studied soils can be deficient in S and NP. In general, soil fertility is a major concern in Ethiopia, and hence sustainable crop yields can be obtained with judicious and balanced use of inorganic and organic resources.

3.2 Yield and Yield Components

Figs. 1a, 1b, and 1c, summarize the response of wheat grain- and TAGB dry-matter- yields and NTsPP to application of N, S and P at W/Gora and G/Silingo sites in Arsi zone. Application of all the nutrients (N, S and P) led to significant ($P<0.001$) increases in wheat grain- and TAGB-yields and NTsPP of the test crop.

Table 3b. Soil test results after crop harvest for the control and only NS treated plots

Ref no.	Farmer field/Site	Treatments (NS), kg/ha	Av.P(pH<7), Bray-I Av.P(pH>7), Olsen (mg/kg)	SO_4-S (mg/kg)
1	WG	CK (N0S0)	0.05	13.14
2	WG	N69S0	1.13	11.89
3	WG	N69S5	0.88	16.09
4	WG	N69S10	0.66	21.94
5	WG	N69S20	0.80	34.88
6	GS	CK (N0S0)	1.43	6.65
7	GS	N69S0	1.56	6.67
8	GS	N69S5	0.61	11.00
9	GS	N69S10	0.34	21.90
10	GS	N69S20	0.28	22.05
11	KTB (Olsen P)	CK (N0S0)	3.46	1.56
12	KTB (Olsen P)	N69S0	2.06	3.03
13	KTB (Olsen P)	N69S5	3.95	3.56
14	KTB (Olsen P)	N69S10	3.33	4.81
15	KTB (Olsen P)	N69S20	2.27	5.70
16	BKJ (Olsen P)	CK (N0S0)	4.11	1.41
17	BKJ (Olsen P)	N69S0	4.75	1.04
18	BKJ (Olsen P)	N69S5	3.20	2.16
19	BKJ (Olsen P)	N69S10	3.80	3.41
20	BKJ (Olsen P)	N69S20	3.90	3.56
21	NS	CK (N0S0)	0.06	1.04
22	NS	N69S0	0.16	1.15
23	NS	N69S5	0.11	2.40
24	NS	N69S10	0.06	2.03
25	NS	N69S20	0.04	2.19
26	BT	CK (N0S0)	0.06	15.65
27	BT	N69S0	0.06	13.02
28	BT	N69S5	0.06	22.49
29	BT	N69S10	0.14	26.96
30	BT	N69S20	0.22	39.58

Key: CK = N0P0S0(kg/ha); N_1 =N = N69P0S0(kg/ha); NS_1 =N69P0S5(kg/ha); NS_2 = N69P0S10(kg/ha); NS_3 = N69P0S20(kg/ha); N_1P_1 =NP =N69P20S0(kg/ha); NPS_1 =N69P20S5(kg/ha); NPS_2 = N69P20S10(kg/ha); NPS_3 =N69P20S20(kg/ha)

There is progressively increasing yield advantage with applying fertilizers at all treatment levels in both fields in the three parameters considered. At W/Gora (heavy black clay, vertisols), there was S response at lower level treatments, i.e. 5-10 kg S/ha, though the initial soils tested adequate for sulfur. Despite, the adequate soils S, before planting, the yield response at this site might be due to the fact that, plant available S of the native soil might have been lost, probably due to factors other than plant uptake in relation to the vertisols physico-chemical dynamics. Therefore, this site may need application of some supplemental amount of S.

But, at G/Silingo, there is yield response to applied N and S at all treatment levels as well as response to P, except that response to P was only apparent at intermediate to relatively higher levels of S (10-20 kg S/ha) (Figs. 1a, 1b and 1c). Sulfur treatments applied at >5 kg S/ha showed significant yield response throughout, particularly at G/Silingo. In this G/Silingo, in general, it is observed that there was better correlation of yield to soil-test values (for N and S), than W/Gora. But, the overall yield at W/Gora was much better than that of G/Silingo, because of the obtained maximum yield. Moreover, there is better positive synergy between applied N, S and P at this site in impacting yields than the W/Gora. In general, at G/Silingo, the yield increase due to applied S and NP at higher levels may indicate that this was not the final level of nutrients that would be applied, as the yield plateau was not reached. But, since the initial soils tested low or marginal, applying S at a rate of 20 kg/ha is reasonable.

Figs. 2a, 2b and 2c summarize the response of wheat grain- and TAGB dry-matter- yields and NTsPP to the application of N, S and P at Keteba and Bekejo sites in E/Shewa zone. In this zone, the application of all the nutrients (N, S and P) also led to significant (P<0.001) increases in wheat grain- and TAGB- yields and NTsPP.

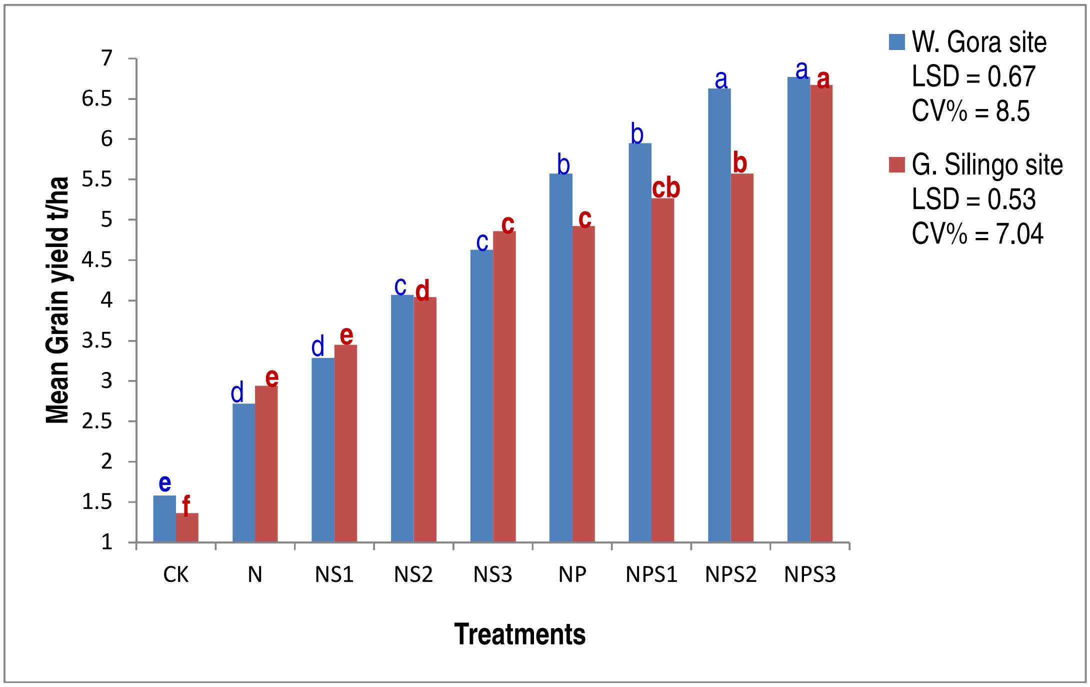

Fig. 1a. Effects of N, S and P application on wheat grain yield at W/Gora and G/Silingo test sites in Arsi zone

*Key: CK = N0P0S0(kg/ha); N_1 =N = N69P0S0(kg/ha); NS_1 =N69P0S5(kg/ha); NS_2 = N69P0S10(kg/ha); NS_3 = N69P0S20(kg/ha); N_1P_1 =NP =N69P20S0(kg/ha); NPS_1 =N69P20S5(kg/ha); NPS_2 = N69P20S10(kg/ha); NPS_3 =N69P20S20(kg/ha), Means bearing same letter(s) within the same column are not significantly different at P<0.1% by T-test. Key: *, **, *** and NS; implies significant at P<0.05, P<0.01, P<0.001 and not significant, at respective probability levels*

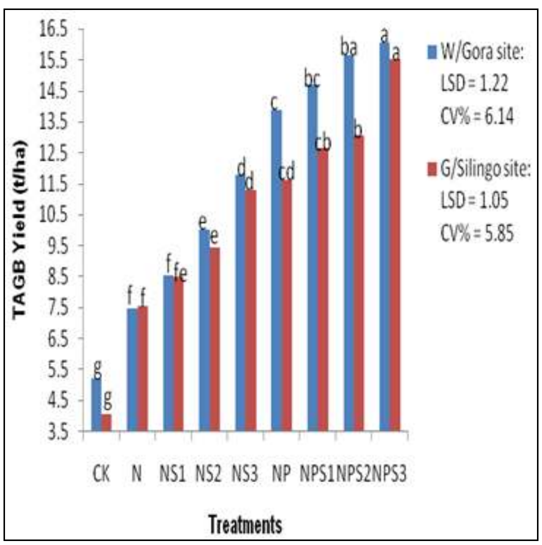

Fig. 1b. Effects of N, S and P application on wheat TAGB yield at W/Gora and G/Silingo sites in Arsi zone

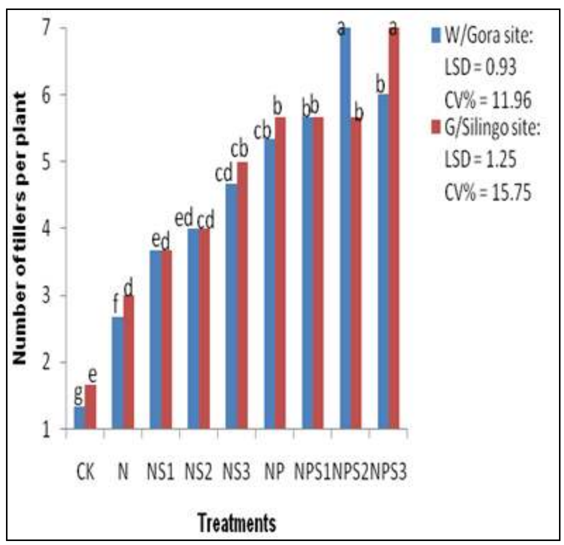

Fig. 1c. Effects of N, S and P application on wheat NTsPP at W/Gora and G/Silingo sites in Arsi zone

*Means bearing same letter(s) within the same column are not significantly different at P<0.1% by T-test. Key: *, **, *** and NS; implies significant at P<0.05, P<0.01, P<0.001 and not significant, at respective probability levels. TAGB =total above ground biomass dry matter yield; NTsPP =number of tillers per plant*

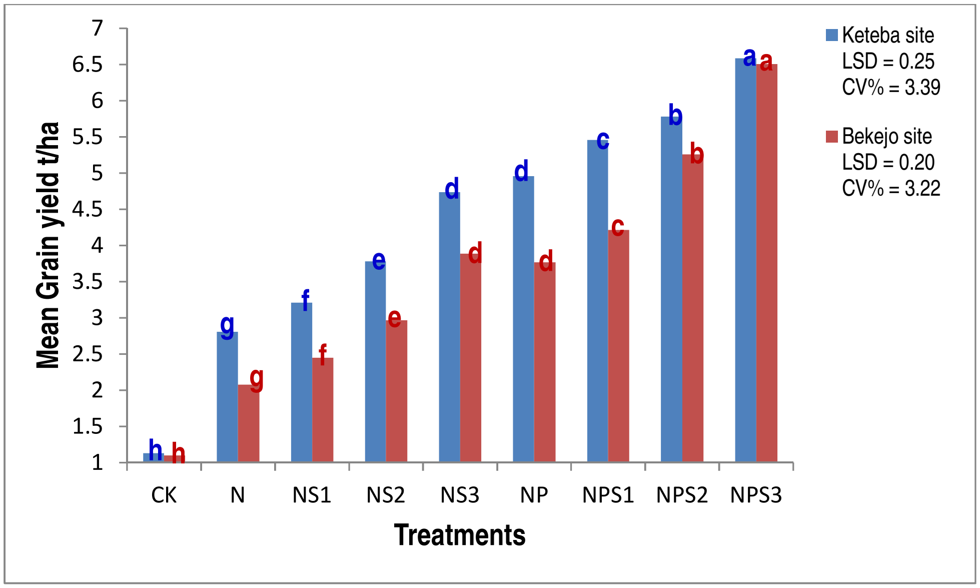

Fig. 2a. Effects of N, S and P application on wheat grain yield at Keteba and Bekejo sites in E/Shewa zone

*Means bearing same letter(s) within the same column are not significantly different at P<0.1% by T-test. Key: *, **, *** and NS; implies significant at P<0.05, P<0.01, P<0.001 and not significant, at respective probability levels*

In general, in this study area, there is yield response to applied S and N but, no response to P in the absence of S; and there is better correlation of yield with soil-test values. Moreover, as noticeable from Figs. 2a, 2b and 2c there is better positive synergy between N, S and P as wheat yields progressively increased with each level of S for both N and NP treatments. However, at both fields, responses to S did not reach a plateau, which implied that higher S levels may increase yield further. In this study area, there is better consistency of yield response to applied fertilizers as compared to Arsi zone. But, when comparing within the study area, still better maximum yield was recorded at Keteba (Calcareous vertisols) than Bekejo. The overall low yield at Bekejo can be attributed to the initial soil-test values at this site, which was slightly lower than that of the Keteba, and at the same time, the sandy clay nature of the soils at Bekejo (Table 3a), which might have caused the loss of available S, probably through leaching before it was absorbed by wheat.

Figs. 3a, 3b and 3c summarize the response of wheat grain- and TAGB dry-matter- yields and NTsPP to the application of N, S and P at N/Suba and B/Tokofa sites in O/Liyuu zone. In this zone too, the application of all the nutrients (N, S and P) led to significant (P<0.001) increases in wheat grain- and TAGB- yields and NTsPP.

In general, yield responses at O/Liyuu follows similar trends as those at Arsi zone. In O/Liyuu zone too, there is an increasing yield advantage with applied fertilizers at each level in both sites in all the variables considered, though may not to mean always statically significant. At both sites, in this zone N and P application significantly increased wheat grain yield and yield components. This is consistent with low soil-test values for both nutrients found on the tested fields (Table 3a). [24] reported similar trend of yield increase of wheat in India.

At B/Tokofa site (heavy clay vertisols), there was significant response to both N and P. Moreover, despite the initial soils-tested adequate for sulfur, yield response, at ≤10 kg S/ha levels was observed in a similar way as W/Gora site of Arsi zone. Regardless of, the adequate levels of soil sulfur before planting, yield response at this site again might be due to the fact that the plant available native soil S might have been lost through factors other than plant uptake, similar as in the case of W/Gora site at Arsi zone. [25], reported, yield response of maize in Malawi, despite the adequate levels of soil SO_4-S, in which case the authors indicated that, SO_4-S was strongly adsorbed particularly in highly weathered soils.

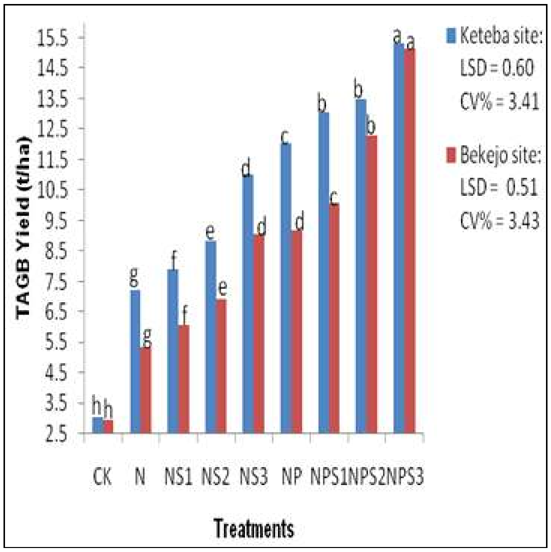

Fig. 2b. Effects of N, S and P application on wheat TAGB yield at Keteba and Bekejo sites in E/Shewa zone

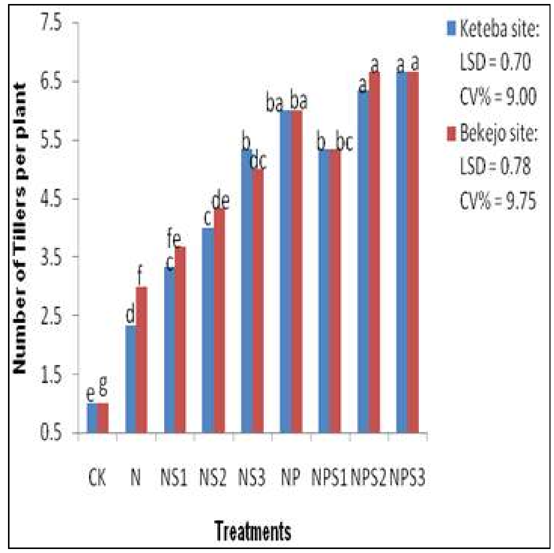

Fig. 2c. Effects of N, S and P application on wheat NTsPP at Keteba and Bekejo sites in E/Shewa zone

*Means bearing same letter(s) within the same column are not significantly different at P<0.1% by T-test. Key: *, **, *** and NS; implies significant at P<0.05, P<0.01, P<0.001 and not significant, at\ respective probability levels. TAGB =total above ground biomass dry matter yield; NTsPP =number of tillers per plant*

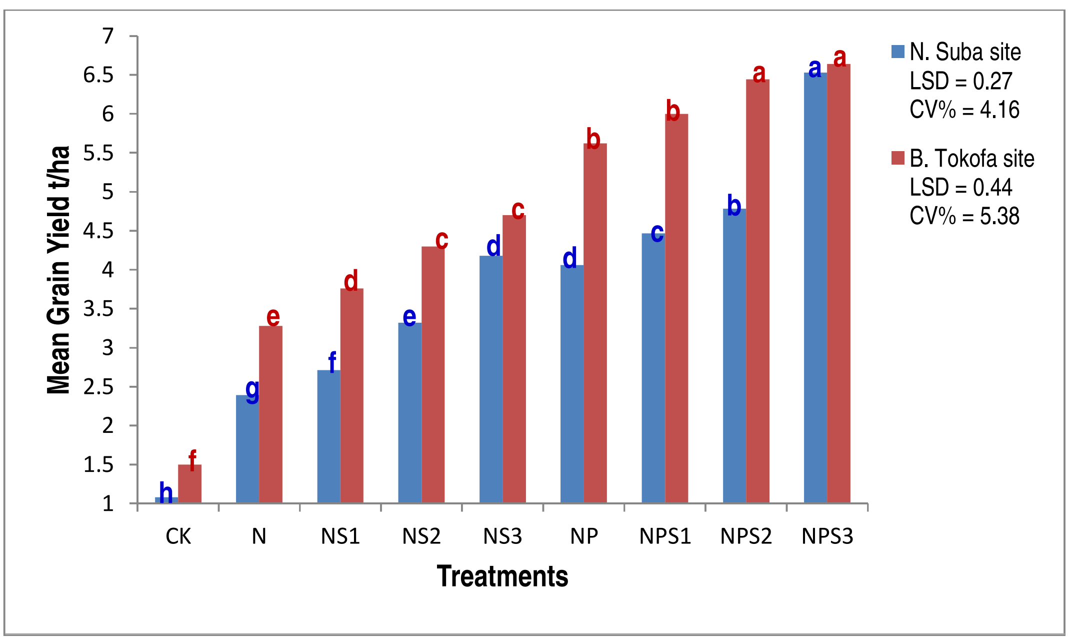

Fig. 3a. Effects of N, S and P application on wheat grain yield at N/Suba and B/Tokofa sites in O/Liyuu zone

*Means bearing same letter(s) within the same column are not significantly different at P<0.1% by T-test. Key: *, **, *** and NS; implies significant at P<0.05, P<0.01, P<0.001 and not significant, at respective probability levels*

At N/Suba, there was better correlation of wheat yield with soil-test values as compared to B/Tokofa, and also better positive synergy between N, S and/or P than B/Tokofa site, but the overall maximum yield at B/Tokofa was much better. At N/Suba site, the wheat yield increase follows a similar trend as that of Keteba and Bekejo of E/Shewa zone, with all types of applied fertilizers. However, the attainment of higher wheat yield at higher treatment levels at N/Suba, again may indicate that this was not the highest level of fertilize treatments that should be applied for wheat production, since maximum response was not reached.

In general, in this set of experiments (i.e., S rate determination trials) too, the wheat cultivar continued to response to applied S from gypsum, in over 67% of the sites, either fully or partially. But, the overall response of wheat to applied fertilizers, especially sulfur, was found to depend on specific sites/soils.

The critical soil (SO_4-S) level determined using Cate and Nelson procedure, from the first set of experiments [26] was, 11.3 mg/kg. Based on this, therefore, in areas like Keteba, Bekejo and N/Suba, which were tested very low in available sulfur and sowed yield response at highest level of sulfur treatments, applying sulfur at >20 kg/ha may be necessary. It is good, because, in applying sulfur at higher rate, rather beneficial effects were reported. For example, [27], reported further increases in loaf volume when sulfur rate was increased up to 100 kg S/ha, while yield responses of wheat were limited to the application of 20 kg S/ha. Similarly, [24], obtained 22-27%, mean grain and straw yields of wheat at 30-45 kg S/ha as compared to control in India. In another field experiments conducted, under rice-wheat system in highly calcareous soil in India, [28] reported significant wheat grain yield increase, at optimum level of S, 60 kg S/ha. However, such a marked increase in yield with added sulfur is reported to be attributed with soils deficient in sulfur when all other factors including rates of NPK and other nutrient elements are optimal. In this respect, the advantage of using such local materials like gypsum can be multidimensional.

In sites like G/Silingo, though wheat continued to responded with applying sulfur, at its highest level, and since the initial soil-tested was marginal, it is reasonable to apply S at a rate of 20 kg/ha for the moment. Whereas, in sites like W/Gora and B/Tokofa, since the initial soils tested adequate for the (SO_4-S), but still wheat showed response to applied sulfur at lower treatment levels, it is therefore, reasonable to apply some supplemental amount of S, at 5-10 kg S/ha.

In general, in comparing the overall wheat yield at each zone, G/Silingo (Arsi), Bekejo (E/Shewa) and N/Suba (O/Liyuu zone), gave low yields as compared to their respective neighbors, W/Gora, Keteba and B/Tokofa. But, if one considers the

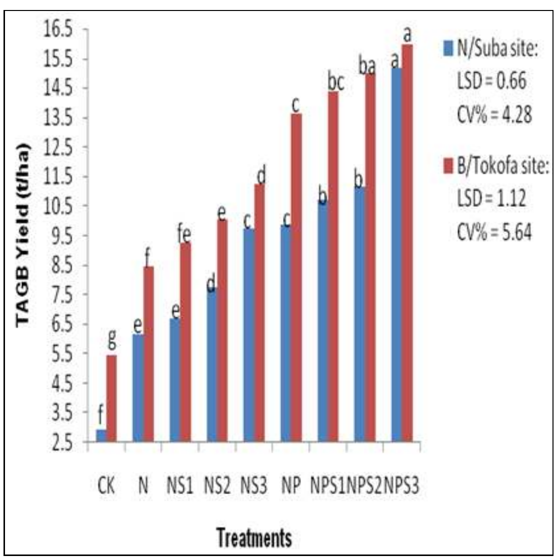

Fig. 3b. Effects of N, S and P application on wheat TAGB yield at N/Suba and B/Tokofa sites in O/Liyuu zone

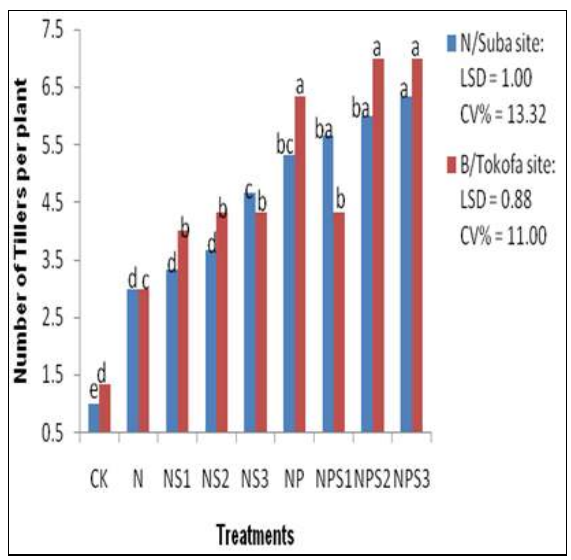

Fig. 3c. Effects of N, S and P application on wheat NTsPP at N/Suba and B/Tokofa sites in O/Liyuu zone

*Means bearing same letter(s) within the same column are not significantly different at P<0.1% by T-test. Key: *, **, *** and NS; implies significant at P<0.05, P<0.01, P<0.001 and not significant, at respective probability levels. TAGB =total above ground biomass dry matter yield; NTsPP =number of tillers per plant* overall yield at each site, Keteba (E/Shewa), Bekejo (E/Shewa) and N/Suba (O/Liyuu) zone, were found to be lagging behind the rest of the sites. But, all results were directly related to soil-test values. Most importantly, when comparing wheat yield in present study with maximum attainable wheat grain cited in literature, there are still large gaps. It is reported that, the genetic yield limit of modern cultivars of wheat can reach up to 8.2-8.5 t/ha [29] with better management practices including adequate supply of nutrients like, sulfur.

Pre-planned pair-wise orthogonal comparisons among treatments using SAS contrast statements for treatments at 95% confidence limits to see the maximum S dose response was performed (data Tables not shown), but can also be seen from Figs. 1, 2 and 3. Responses to S are easily overlooked when P is applied as TSP, a high analysis fertilizer, reported to contain 2-6% S [30]. Though the wheat responded to applied S in over 67% of fields/sites, the response from S that is expected from TSP didn't show this, because all soils tested low in phosphorous. Therefore, the chance of S response expected from TSP might have been obscured due to the inherent low P status of soils(Table 3a). This can be seen by looking at only S responsive, but non-P responsive sites like G/Silingo. In such sites, there is yield response with applied N and S at all treatments, except for S that is expected to come from TSP, which can be noticeable from yield between treatments (NPS_3 -NS_3) (Figs.1, 2 and 3).

Furthermore, from the study it is noticeable that with applying N, there was a sharp-rise in wheat yield graphs, in all zones, including non-S and non-P responsive ones in the agronomic variables considered (Figs. 1, 2 and 3). For instance, 72.15% to 148.67% grain yield advantage over control was recorded in six sites, with applied N. Indeed, this sharp-rise in yield with N, is indicative of the fact that N is still the most limiting element followed by P and S for wheat production. This is due to the fact that, Ethiopian soils are severely low in available N, which in turn may be due the low levels of OM in soils, vis-à-vis the dynamics of OM or N in tropical climate and soil conditions.

4. CONCLUSIONS AND RECOMMENDATIONS

In this set of experiments too, wheat responded to applied S and NP; and the responses were found to depend on site/soil conditions. Therefore, site specific sulfur recommendations can be made. The critical level (CL) of soil SO_4-S, estimated in the first set of experiments was, 11.30 mg/kg. Based on this, in such sites like Keteba, Bekejo and N/Suba, which showed highly significant response to applied sulfur, the sulfur rate can be slightly >20 kg/ha. This is reasonable, because the initial soils tested very low for SO_4-S, and at the same time the nutrient response curve was not reached. But, for the moment farmers in such areas can be advised to apply 20 kg S/ha with recommended dose of NP as provisional recommendation for increasing wheat yield or for reducing quality loss. At G/Silingo, since wheat showed significant response to the applied sulfur, and the pre-soil tests showed low/medium, applying sulfur at a rate of 20 kg/ha with recommended dose of NP is advisable. Whereas at W/Gora and B/Tokofa sites, since the initial soils tested adequate for SO_4-S, but, since wheat showed yield response at lower levels, i.e., 5-10 kg S/ha, it is reasonable to supplement about, 5-10 kg S/ha. But, in such areas, small holding farmers can also opt for better OM management coupled with good agronomic practices. Since, in all the studied sites, maximum attainable wheat grain yield reported by other workers was not achieved, it is important to make further investigations by controlling all factors of production including other nutrients like Zn, for it tested low to marginal in all studied soils from the first season experiments. In general, if similar traditional agricultural practices continue to exist in Ethiopia, the problem of S and/or NP, is projected to be more severe in the near or far future. Therefore, close monitoring of S and NP deficiency including other essential elements through initial soil testing is imperative. The study revealed also that, N was found to be very low in all areas. This indicates that N management followed by SP is critically important in sustaining wheat production in the country.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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