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Wheat Response to Applied Nitrogen, Sulfur, and Phosphorous in three Representative Areas of the Central Highlands of Ethiopia -I

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Authors' contributions

This work was carried out in collaboration between all authors. Author AM designed the study, performed field experiments, managed Lab. analysis, and wrote the first draft of the manuscript. Authors JMRS and TM wrote the protocol, edited the data, reviewed and edited the manuscript. Author NA reviewed and edited the manuscript and managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

Eighteen explorative field experiments were conducted in 2012/2013 seasons in three representative areas in central highlands of Ethiopia, to evaluate the effects of sulfur (S) vis-à-vis nitrogen (N) and phosphorous (P) on wheat. Furthermore, an assessment was made on the status of sulfur in soils/plants. Two levels of S(0 and 20 kg/ha); 2 levels of P(0 and 20 kg/ha); and 2 levels N(0 and 69 kg/ha) were used as gypsum, triple-superphosphate (TSP) and urea respectively. Randomized complete block design (RCBD) was used as an experimental design in three replications. Statistical analysis using SAS showed significant response (P<0.001) in grain and

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other yield components of wheat. All studied fields showed full-response (100%) to applied N, as directly related to soil-test values. Likewise, 72.3% of fields/sites showed response to S. Similar as N, all fields tested low in available P, but 78% showed response to applied P. Good relationship between soil-test values and crop-response for N and S was observed. But, for P in some fields inconsistencies exist. TSP reported to contain 2-6% by weight of S, however, pair-wise comparisons didn't reveal yield response beyond 20kg S/ha. In the study, it is learnt that light textured and calcareous vertisols in the peripheries of rift-valley were found to be more deficient in S. There are strong indications that, S response/deficiency which is now observed in central highlands can be widespread, if such assessments were made across the country, especially far into out fields. Therefore, it is important to include S, in the balanced fertilizer formula. Indeed, for the smallholding farmers it is imperative to sustainably build soil organic carbon (SOC) stocks close to critical levels. It is also important to augment inorganic and organic fertilizers with local S sources (e.g., gypsum) to take advantage of integrative benefits and/or to economize fertilizer use.

Keywords: Sulfur response; gypsum; grain yield; sulfate sulfur; wheat cultivar.

1. INTRODUCTION

Ethiopia is the largest producer of wheat in sub-Saharan Africa (SSA), over 1.8 million hectares annually [1]. Wheat ranks third in area coverage and total production after Teff and maize, and after maize and sorghum for productivity. However, to ensure sustainable crops production including wheat, healthy soils are important, soils with good physical, chemical and biological fertility. In contrast, poor health/quality soils exhibit various dysfunctional attributes like deficiencies in nutrients, erosion and various other constraints. Plant nutrients are key components of soil health/quality and are good, if present in adequate, but if not, the means of replenishing them must be weighed against any economic activity.

For the last three decades, Ethiopian agriculture depended solely on imported fertilizer products, only urea and di-ammonium phosphate (DAP), sources of N and P. However, recently it is perceived that the production of such high protein cereals like wheat and legumes can be limited by the deficiency of S and other nutrients. In Ethiopia, major prone areas of S deficiency are the central highlands (HLs), because of their high crop production, which is driven by high market access in the big towns/cities in the center of the country. Reasons that lead to S deficiency in soils of central HLs include 1) improved use of high-analysis fertilizers that contain no S, 2) intensive agriculture that leaves behind little organic matter (OM), and/or complete removal of OM for alternative uses, including farm yard manure (FYM), 3) increased crop yields due to high yielding varieties, resulting in more S removal, and 4), intensive cropping-systems that include legumes and oil crops that mine more S etc.

Although sulfur is often overshadowed by N, P and potassium (K), it is an essential element 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), that impact nutritional value of human food and feeds, contain sulfur [2]. Sulfur is reported to be a macro-nutrient that is taken-up by crops in amounts similar to and sometimes exceeding those of P, 10-30 kg/ha [3], and considered to be one of the most limiting nutrient element for crop production. It is essential not only for plant growth and quality produce, but also enhances other nutrients use efficiency and ranks second only to N in importance for optimum crop yield/quality [4].

However, S is a nutrient most overlooked in Ethiopian agriculture. In Ethiopia, incidental addition of S from low-analysis sources is nil due to a shift to high-analysis fertilizers. It is true that farmers and extensionsts can aim at increasing crop yields only in quantity by applying significantly higher amounts of NP from urea and DAP. But, in such conditions, failure to supplement S in balanced-fertilizer programmes can rapidly deplete available soil reserve leading to hidden S deficiency. Regardless of its importance, very little research is done on the status in soils and crops, and the available information/data are quite scanty. Moreover, unlike NPK and other elements, S is not routinely analyzed in soil and plant tissues at the laboratories (Labs) in Ethiopia.

Therefore, this study was aimed at investigating the response of wheat to applied S in relation to NP in different agro-ecological zones (AEZs) and soils in central highlands of Ethiopia. Specifically, this study aimed at quantifying the status of S in relation to other soil fertility parameters in selected wheat growing areas. The possible questions intended by the treatment structure can be a) is there a response of wheat to applied N, S, and/or P? b) Is there a combined effect of N, S and P on wheat yield and/or yield components?

2. MATERIALS AND METHODS

2.1 Description of the Study Areas

In Arsi(Ar) zone/area, the average annual rainfall during growing season is 788-1200mm. Mean annual potential evapo-transpiration, calculated by pan-evaporation is about 1300mm. Mean annual maximum and minimum temperatures are 23°C and 10°C respectively. It has low relief difference with altitude range, 1769-2418m above sea level. In some places where the slope is flat, flooding and water-logging occurs. In the area, a considerable proportions of vertisols exist [5]. The upper soil layer consists of tephritic materials, whereas substratum is calcareous, enriched through secondary precipitation over the bedrock [5].

In East Shewa (ES) zone, the average annual temperature ranges from 8-20°C. The AEZs extends from sub-tropical and mid-highlands to highlands. The area also has low relief difference with altitude range, 1874-2427 m. In general, the average annual rainfall during the growing season is about 800-1200 mm. Dominant soil types are vertisols [6], and the geology is typically alkaline basalt and trachyte of the Cenozoic volcanic eruptions.

Oromia Liyuu (OL) zone, has an altitude range of 2124-2350 m. The mean annual rainfall is 1078mm. Main rainy season extends from June to September, which receives 70% of the annual rainfall. The mean minimum and maximum temperatures were 6.2°C and 22.1°C respectively, with mean relative humidity, 60.6%. Major soils of the area are nitosols and vertisols; and the major AEZs of this area extend from extremely cool to mid-highlands, 61 and 39% respectively.

In each administrative zone/study area six sites/farmers fields were selected, and geo-referenced using Global Positioning System (GPS), assisted by Google earth (2011) and were classified by elevation 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 in wheat. The specific locations and salient features of selected field/sites are presented in Table 1.

2.2 Experimental Design

Twenty four field experiments were conducted in 2012 and 2013 cropping seasons in central HLs of Ethiopia, representing wheat growing districts in Arsi, E/Shewa and O/Liyuu administrative zones, covering different AEZs/soil types.

During the first year, 18 explorative experiments were conducted in 18 farmers' fields, six in each zone/study area. A newly released wheat cultivar, known as ("Kekeba"), was used as a test crop. Evaluated nutrients applied were, 2-levels of S(0 and 20 kg/ha), 2-levels of P(0 and 20 kg/ha), and 2-levels N(0 and 69 kg/ha), as gypsum, TSP and urea respectively. The nutrients were combined in four treatment levels designated as check (CK) (no fertilizer), N, NS and NPS. The experimental design used was randomized complete block (RCBD) in three replications. Each replication was sub-divided into 3 m x 5 m = 15 m^2 plots, making 4 experimental units per block. One third of N was incorporated within rows just before seeding, whereas the remaining 2/3 was top-dressed at tillering. But, the entire source of S and P were drilled within rows and incorporated into soils just before seeding. The agronomic spacing for wheat between rows and plants, 25 cm x 5 cm was used. There were 12-rows of wheat per plot. There were two border rows and one row, 25cm x 5cm was used for plant tissue sampling. The remaining center rows, a 4 m x 1.5 m used for agronomic/yield data and seed sample collection. In both seasons, during the crop's growing stage or before/after harvest agronomic parameters such as number of tillers per plant (NTsPP), plant height (PH), spike/panicle length (SPL), spike/ panicle weight (SPW), total above ground biomass (TAGB) dry matter, forage/stover yields (SY), number of seeds per panicle (NSsPP) and grain yield (GY) were recorded. Plant samples were collected from each plot at booting for analysis. In doing so, wheat tissue were collected from the upper 1/3 of plants from 25 plants from a row. After sampling the tissues were rinsed quickly in distilled water right in fields and shaken to dry and placed in paper bags and air-dried in dust-free rooms. Then, in Labs samples were oven dried at 65-70°C for 48 hrs. Grain/stover samples were also collected at harvest and dried similarly. All samples (tissue at booting, and grain/stover), thus oven-dried were ground using Tecator-CYCLOTEC-1093 sample mill and saved for total nitrogen(TN), total sulfur (TS), TN/TS ratios, S-uptake, and critical levels determination.

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

Site/farmer field	Lat.(N)		Long.(E)		Altitude	Soil type
	Degree	mm.mm	Degree	mm.mm	m	
Abosara-Alko (A/Alko),(AA)	7	49.454	39	1.661	2297.02	Light vertisol
Dosha,(Do)	7	53.813	39	6.176	2418.32	Nitosol
Gora-Silingo (G/Silingo),(GS)	8	0.792	39	8.436	2151.10	Light vertisol
Chefe-Misoma (C/Misoma),CM	7	59.067	39	3.964	1768.98	Nitosol
Boneya-Edo (B/Edo),BE	8	3.507	39	17.184	2359.95	Light vertisol
Boru Lencha (B/Lencha),(BL)	8	7.476	39	17.722	2186.37	Nitosol
Chefe Donsa (C/Donsa),CD	8	57.113	39	6.087	2426.53	Pellic vertisol
Keteba(Ke)	8	53.553	39	1.913	2224.37	Pellic vertisol
Ude(Ud)	8	40.767	39	2.197	1873.86	Pellic vertisol
Bekejo(Bk)	8	38.376	38	55.322	1874.16	Pellic vertisol
Insilale(In)	8	51.647	38	53.214	2211.30	Light Vertisol
Kilinto(Ki)	8	54.099	38	49.133	2204.00	Pellic vertisol
Nano Kersa (N/Kersa),(NK)	8	55.605	38	31.062	2123.74	Light vertisol
Nano Suba (N/Suba),(NS)	8	57.287	38	29.756	2229.54	Nitosol
(Berfeta Tokofa) B/Tokofa,(BT)	8	59.605	38	30.98	2252.64	Nitosol
Dawa Lafto, (D/Lafto),(DL)	8	59.147	38	26.92	2173.60	Nitosol
Wajitu Harbu (W/Harbu),(WH)	9	1.457	38	28.731	2335.63	Nitosol
Tulu Harbu (T/Harbu),(TH)	9	2.571	38	28.817	2349.62	Nitosol

The soils are classified as characterized/described by [5,6]

Table 2. The Analytical method of some soil parameters of the studied fields

Parameters	Unit	Extraction/Analytical method by	References
pH	NA	Potentiometrically,1:2.5 soil:water solution	[7]
EC	mS/cm	1:5 soil:water suspension	[8]
Exch.bases (Na^{+1}, K^{+1})	cmol(+)/kg	1*M* NH4OAc solution, pH =7.00	[9]
Exch.bases (Ca^{+2}, Mg^{+2})	cmol(+)/kg	1*M* NH4OAc solution, pH =7.00	[7]
CEC	cmol(+)/kg	1*M* NH4OAc solution, pH =7.00	[7]
PBS	%	Calculation from exch. bases	[7]
TN	%	Kjeldlehl as described in	[10]
OC	%	Walkley-Black as described in	[11]
Av.P	mg/kg	Bray-I, (pH<7.00)	[12]
Av.P	mg/kg	Olsen, (pH>7.00)	[13]
SO_4-S	mg/kg	Calcium Ortho-Phosphate, Turbidimetric	[9]
Soil texture	NA	Hydrometer method	[14]

NA=Not applicable

2.3 Soil Sample Preparation and Analysis

Before planting, composite soil samples representing each block from 10 spots were taken, 0-20 cm depth and bulked together and further composted to represent one sample per farmer-field. The soils were air-dried immediately in dry-rooms to avoid sulfate formation from OM in transit. Dried soil samples were ground and sieved to pass through 1-mm sieve and transported to Tanzania for evaluating physico-chemical fertility. Soil samples were analyzed for pH, electrical conductivity (EC), Exchangeable bases [calcium (Ca^{+2}), magnisium (Mg^{+2}), sodium (Na^{+1}) and potassium (K^{+1})], cation-exchange capacity (CEC), base saturation (PBS), total nitrogen (TN), organic carbon (OC), available phosphorous (Av. P), sulfate (SO_4-S) and soil texture, in wet-chemistry lab at Sokoine University of Agriculture (SUA), following the procedures outlined in (Table 2).

2.4 Statistical Data Analysis

Yield and yield components data were analyzed using SAS procedure [15]. Analysis of variance (ANOVA) was done using PROC-MIXED of generalized linear model (GLM) procedure of SAS protocols to evaluate differences between treatments in different variables. When differences between treatments were significant, least significant difference (LSD) was used to separate means, with a significant level of 0.1%, 1% and 5%. Variables like yield and yield components were also evaluated by correlation/regression and slopes were compared through parallelism and coincidence test using PROC-REG procedure. Also, pre-planned pair-wise orthogonal comparisons among treatments using SAS contrast statement were performed.

3. RESULTS AND DISCUSSION

3.1 Selected Physico-Chemical Properties of Soils

Table 3 presents some physico-chemical variables of soils of the study field/sites cultivated for wheat before planting. The sites varied widely in their physico-chemical properties, particularly pH, CEC, PBS and SO_4-S, which can be attributed to specific agro-climatic conditions of the areas.

The pH ranges from strongly to moderately acidic, (5.1-6.7), in O/Liyuu zone; to strongly acidic to near neutral, (5.3-7.0) in Arsi; to neutral to moderately alkaline, (7.1-8.2) in E/Shewa zone. In E/Shewa most of the soils were calcareous with fragments of calcium carbonate ($CaCO_3$), and hence were alkaline in reaction. Such sites include, C/Donsa, Keteba, Kilinto and partly Bekejo, which is making 67% of the fields/sites in the zone. But, in all studied areas, the pH values fallen within a range 4.5-8.5 reported by [16] for agricultural soils, with the values, 5.5-7.0 preferred by most crops and pastures. In only two sites, namely Dosha and B/Tokofa, the pH was below 5.5 (Table 3), but tolerable for wheat.

The EC that range, 0.05-0.25(mS/cm) indicates that the studied soils were salt free based on the criteria developed by [16]. The CEC ranges from 15-47.8 cmol(+)/kg, and falls within a range 15-25 cmol(+)/kg soil suggested to be medium; and 25-40 cmol(+)/kg high based on the criteria developed by [17] for tropical soils.

The exchangeable cations were in the order: $Ca^{+2} > Mg^{+2} > K^{+1} > Na^{+}$. Calcium is observed to be dominating the exchange sites followed by Mg, and largely controls the base saturation and pH. Such soils are more prominent in East Shewa, which were calcareous in nature, but was not to the level that can significantly affect the availability of plant nutrients, like P for arable crops/plants.

The PBS ranged from 42.48-71.83% in Arsi falls in a range considered medium to high; and that of E/Shewa, ranging from 90.80-96.64% falls within a range considered to be high; and that in O/Liyuu zone, ranges from 41.60-66.98% falls within a range considered to be medium to high based on the criteria developed by [17,16] for tropical soils. The PBS range, 20-60%, is considered medium, and suggested to represent less fertile; whereas that >60%, is considered to be high, and suggested to be indicating the better soil fertility [17].

The TN, ranging from 0.06-0.25% falls in a range considered to be very low to low, based on [17,16] for tropical soils. This low TN can be attributed to the low levels of SOC in the studied soils, and this can adversely affect crop yields.

The available P extracted by (Olsen method) for E/Shewa, ranged between 7.55-10.99 mg/kg, is far below 10-20 mg P/kg a range considered low [16] and <20 mg P/kg considered low by [18].

Similarly, the Bray-I P for soils from Arsi and Oromia Liyuu zones, ranging from 0.22-5.12 mg/kg are far below the low level of Bray-I P, <20 mg/kg by [18]. According to [17,19], in such low P status soils responses to applied P is most likely expected.

The SO_4-S, ranged from 1.30-24.18 mg/kg and over 72.3% of the fields were found to be below 10mg SO_4-S/kg a critical level suggested by [20], and may be S limiting.

The SOC contents of the studied soils, 0.90%-2.99%, falls in a range considered to be very low to low and/or marginal based [16]. The SOC of most studied sites/soils, about 78% are far below the critical threshold of 2%, suggested by other workers [18,20]. At Dosha site, in Arsi zone, it was 2.04%, just equilibrating the critical level. From all sites, only C/Misoma, B/Edo and W/Harbu had the SOC slightly above this critical level. As a direct link to soil-test values in these sites wheat crop didn't respond to the applied S.

Indeed, as this critical level separates only low and high values, the marginal/medium levels of OC can stretch up some points above 2%. Considering this, therefore, about 83.3% of the studied field/sites can be regarded as low in OC. This may indicate that some of the key soil quality/health indicators like structural stability of the studied soils could be at risk. [21] reported that up to 98% of total soil sulfur in sub-humid Ethiopian highlands may be present as organic S compounds. Soil OC is also reported to be a promising indicator for guiding N fertilizer management/use under challenges of soil heterogeneity among smallholder farming systems given its integrative benefits that lead to high N supply and soil quality [20]. Furthermore, SOC is described as a ‘universal keystone indicator’ in soil fertility management [22,23], making it a good candidate and an appropriate tool for managing soil fertility heterogeneity among farmer fields in SSA, a region with the lowest fertilizer use [24], and N use efficiency in the world [25,26].

Table 3. Physico-chemical features of the soils of the study areas before planting

Study Area/Zone	Farmer Field	pH Soil:H_2O	EC (mS/cm)	Exchangeable bases Ca^{2+}	Mg^{2+}	Na^+	K^+	CEC (Cmol(+)/kg)	PBS (%)	TN (%)	OC (%)	Av.P (mg/kg)	SO_4-S (mg/kg)	Soil Texture
				(cmol(+)/kg)										
Ar	AA	6.0	0.10	10.74	2.70	0.04	1.56	23.8	63.20	0.13	1.11	5.12	6.94	SCL
Ar	Do	5.3	0.10	7.55	1.44	0.23	1.10	24.3	42.48	0.25	2.04	1.84	10.44	C
Ar	GS	6.1	0.11	12.52	3.25	0.23	1.27	25.3	68.24	0.14	1.17	3.73	7.77	SC
Ar	CM	6.9	0.08	13.76	5.64	0.28	3.02	31.6	71.83	0.13	2.75	1.11	22.13	C
Ar	BE	6.2	0.08	11.45	4.03	0.23	2.09	27.8	64.03	0.20	2.77	1.95	21.50	C
Ar	BL	7.0	0.07	13.94	4.62	0.27	1.78	29.8	69.19	0.11	1.07	3.29	4.32	SC
ES	CD	8.0	0.19	33.90	7.33	0.38	1.89	45.01	96.64	0.06	0.90	7.67	15.37	C
ES	Ke	8.1	0.25	29.65	8.77	0.28	5.49	45.8	96.47	0.06	1.06	7.55	5.78	C
ES	Ud	7.1	0.06	26.10	6.06	0.29	3.32	39.4	90.80	0.10	1.23	9.53	12.37	C
ES	Bk	7.3	0.08	23.97	5.28	0.47	2.40	34.4	93.39	0.07	1.31	10.82	1.30	SC
ES	In	7.2	0.08	21.13	5.58	0.28	2.09	31.4	92.65	0.10	1.35	10.99	6.62	C
ES	Ki	8.0	0.24	32.48	8.53	0.32	4.18	47.8	95.23	0.06	1.39	8.17	8.27	C
OL	NK	6.7	0.07	11.45	3.85	0.29	2.09	26.4	66.98	0.07	1.41	0.22	11.89	C
OL	NS	5.7	0.07	3.48	1.21	0.19	1.99	15	45.73	0.13	1.47	0.39	5.64	C
OL	BT	5.1	0.06	3.65	1.33	0.16	1.68	16.4	41.60	0.12	1.69	1.89	3.82	CL
OL	DL	5.9	0.05	5.96	1.39	0.30	2.19	18.6	52.91	0.14	1.71	0.28	10.83	CL
OL	WH	5.5	0.08	3.83	1.15	0.17	2.30	15	49.63	0.15	2.99	1.34	23.02	C
OL	TH	5.6	0.08	5.96	2.11	0.18	2.91	22.2	50.25	0.14	1.31	1.45	24.18	C

Key: Study Areas (Ar =Arsi, ES =East Shewa, OL =Oromia Liyuu); Soil Types (CV =Chromic Vertisol, Ni =Nitisol, PV =Pellic Vertisol); and Soil Texture (SCL =Sandy clay loam, C =Clay, SC =Sandy clay, and CL =Clay loam).
Av P = Available phosphorus

From the current study it is noticeable that, in about 83.3% of studied fields, SOC is very low. Therefore, it is not surprising that the studied area can be low/deficient in N, S and/or P status. A root cause for the low OC, is the farming systems of the areas. From a transect survey conducted in over 325 households and/or farm-fields, it was observed that the crop residues which are the potential sources of nutrients have alternative uses, cattle feed and fuel etc. Even during crops' growing period, larger amount of plant biomass are removed from farmlands, in the form of weed/feed. This indicates that restorative measures, that can lead to an acceptable minimum SOC level are needed, especially for those elements never applied in the form of inorganic fertilizers, (e.g., sulfur).

With respect to the soil texture, in most areas, clay classes dominate. But, whenever there is sandy-clays dominate as in the case of G/Silingo, B/Lencha and Bekejo sites, responses to applied sulfur where pronounced as the extractable SO_4-S were inherently low.

3.2 Response of Wheat to Applied N, S and P

With the history of soil fertility management for crop production, in relation to past and present inorganic fertilizer use and cropping-systems and the consequent nutrient depletion through continuous cultivation calls for better knowledge of soil nutrient status, particularly for those never applied in the form of inorganic fertilizers. The current study focused on making an assessment on the status of S in soils and plants in central HLs of Ethiopia. The data for grain yield for the experiments conducted in diverse AEZs and soil types are presented in (Figs. 1, 2 and 3).

The grain yield and other yields components of wheat all showed highly significant response ($P<0.001$) among treatments with applied N, S and P. Moreover, the obtained wheat yield response was better related to other yield attributes and soil-test values. For instance, grain yield (GY) is well correlated to TAGB(r = 0.88), SY(r = 0.82), SPW(r = 0.76), SPL(r = 0.65), PH(r = 0.53), NTsPP(r = 0.67), NSsPP(r = 0.40), and sulfur uptake in grain(r = 82). The level of significance of each was at ($P<0.0001$), ($P<0.0001$), ($P=0.0003$), ($P=0.0034$), ($P=0.0246$), ($P=0.0023$), ($P=0.051$), and ($P<0.0001$) respectively. Grain yield is also positively correlated to the native soil's SO_4-S and TN before planting (r=0.69), and (r=0.51), with the degree of association ($P=0.0033$) and ($P=0.0327$), respectively.

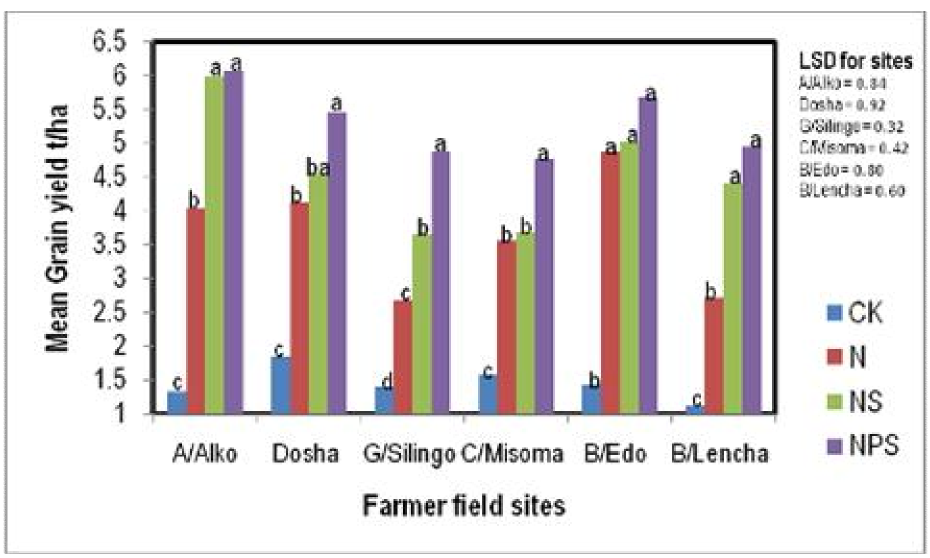

Fig. 1. The mean separation of wheat grain at Arsi zone

Means bearing same letter(s) within same group are not significantly different at P< 0.01% probability level by T-test

*Key: *, **, *** and NS; implies significant at P<0.05, P<0.01, P<0.001 & not significant, respectively probability levels*

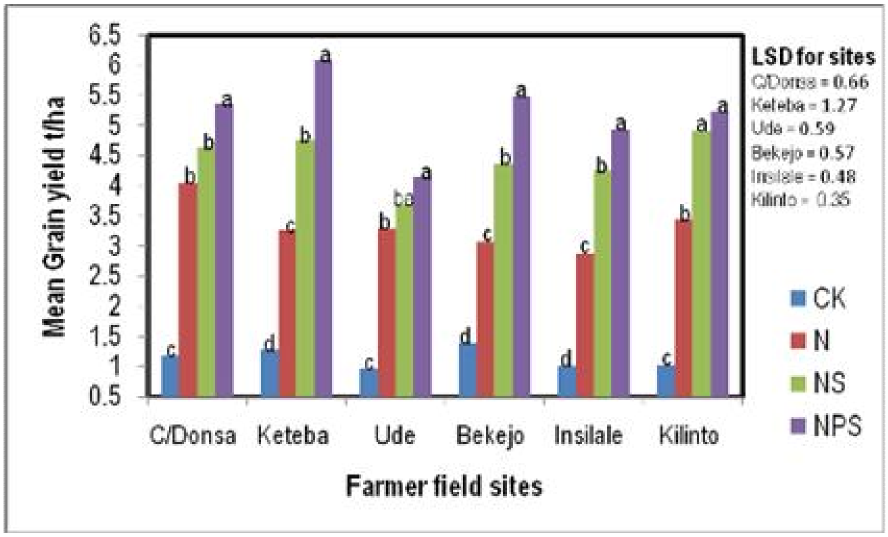

Fig. 2. The mean separation of wheat grain at the East Shewa zone

Means bearing same letter(s) within same group are not significantly different at P< 0.01% probability level by T-test

*Key: *, **, *** and NS; implies significant at P<0.05, P<0.01, P<0.001 & not significant, respectively probability levels*

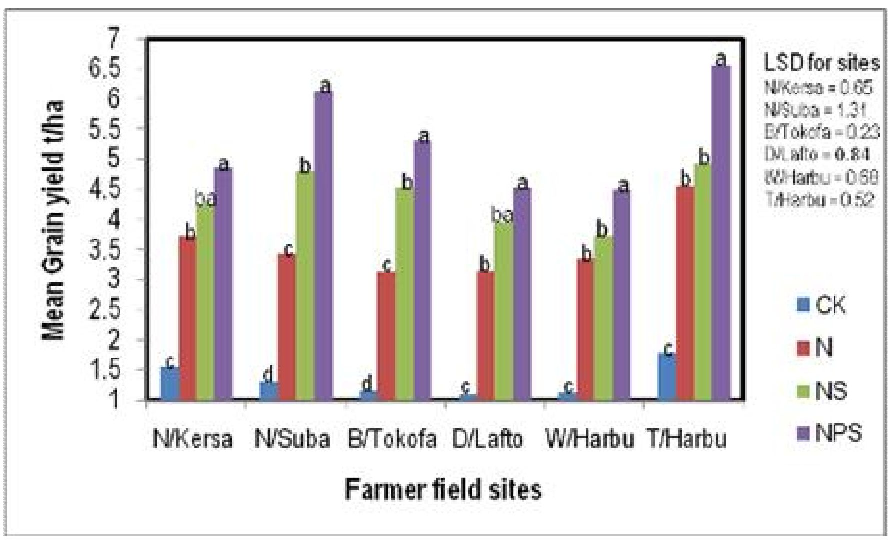

Fig. 3. The mean separation of wheat grain at the Oromia Liyuu zone

Means bearing same letter(s) within same group are not significantly different at P< 0.01% probability level by T-test

*Key: *, **, *** and NS; implies significant at P<0.05, P<0.01, P<0.001 & not significant, respectively probability levels*

It was observed that, in all the studied fields wheat showed highly significant response to applied N (100%), and this is directly related to soil-test values (Table 3). Similarly, all studied fields were low/marginal in available P, however, 56% of the fields showed full-response and 22% marginal response to the applied P. The sites which did not show response to P in relation to the next lower level treatment (i.e., NS) in proportion were A/Alko, B/Edo, B/Lencha, and Kilinto, making 22.2% of all the sites. But, it is important to note that all the fields can be responsive, if compared to CK and only N treatments, as was observed in the second season experiments. There was lesser P response than N, regardless of the low levels of the initial soil test P values. But, it is well recognized that, complex soil processes influence, which may necessitate determining the ability of soils to release natural/applied P for plants [27]. Moreover, there can also be negative synergy between the applied P and S. This may indicate the need for better P management (e.g., rate, method and timing of application including for soil build-ups).

From the 18 study fields, maximum wheat grain yield 6.6t/ha was obtained in only one field, T/Harbu site (Fig. 3). However, it is reported that an average crop of wheat with a grain yield of over 8.5t/ha were achieved in UK, when major nutrients N, P, K and S etc are interacting [28]. This may indicate that the genetic limit of the tested wheat can be higher, when major crop management inputs and decisions are optimized.

In the study, 50% of studied fields gave full-response to S from gypsum and 22% had marginal-response, and there observed good correlation of S response to soil-test values following N. The least yield response was observed for P (Figs. 1, 2 and 3). As a direct link to this, SO_4-S in the studied fields/soils range, 1.30-24.18 mg/kg. Based on 10mg/kg $CaCl_2$-extractable SO_4-S as a critical limit of deficiency for most crop species reported by [19], therefore over 50% could be S deficient. More interestingly, in relation to wheat S need, [29], suggested a more crop-specific critical range, 10-13 mg/kg SO_4-S, for cereals (wheat, maize) and oilseed (mustard). Considering this, however, 72% of the studied fields can be regarded as S limiting for wheat production (Figs. 1, 2 and 3). In general, the S deficiency of soils can be much severe, if one may move far into out fields.

Not only the farming system, but also the cropping system can be the root cause of S deficiency. From sideline survey study made in over 325 households/farm fields it was learnt that, all farmers use crop-rotation (legumes/oil crops with cereals) as an indigenous soil fertility management and/or weed control. But, pulses and oil crops are expected to mine more S than cereals, because S and N are needed for protein synthesis and oil formation, and this can further lead to the depletion of natural soil reserve that can aggravate sulfur deficiency.

From the Figs. 1, 2 and 3, it is noticeable that, in all studied sites, the grain yield graphs/curves were always rising with any additional type and level of fertilizer applied, resulting in a grain yield advantage, which may indicate the synergy between the applied fertilizers. These always rising graphs may also indicate that this was not necessarily the economic optimum level possibly for NP, as the nutrient response curve was not obtained, though in some sites the increase was not at an increasing rate. This may indicate, higher economic benefit with the application of highest NPS treatments levels.

In general, in E/Shewa there was better S response, followed by O/Liyuu zone, Arsi being the least. Moreover, in E/Shewa (Bekejo), the lowest SO_4-S(1.3 mg/kg), was recorded. Even at Arsi, with lower S response, very low SO_4-S in soils, 4.32mg S/kg was recorded in B/Lencha. Indeed both sites are found in the periphery of the rift-valley. Furthermore, the soils of both sites were sandy clay. This may indicate that, the calcareous soils, low in OM in the peripheries of rift-valley are expected to be much deficient in S. In agreement with this [30], reported significant yield responses of wheat to S, particularly in areas of low S deposition and with light-textured or shallow calcareous soils in England.

Pair-wise orthogonal comparisons among treatments using SAS contrast statements for treatments at 95% confidence limits was done (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 [3]. Though the wheat responded to applied S in 72% 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 3). This can be known by looking at only S responsive, but non-P responsive sites such as A/Alko, B/Lencha, Kilinto and D/Lafto, which were indicated by the non-significant negative confidence limits at 95% (data not shown).

In general, from (Figs. 1, 2 and 3), it is learnt that in all studied sites, with the applied N, there was a sharp rise in grain yield, including B/Edo (a site non-responsive both to S and P). This sharp rise in grain yield with applied N, may be indicative of the fact that, N was the most limiting followed by P, which in turn may be due low SOM in the tropical climatic conditions.

4. CONCLUSIONS AND RECOMMENDATIONS

From the study, it is revealed that the wheat responded well to applied N, S and P, and there exist highly significant difference among treatments (*P*<0.001%) in the grain, and other yield components of wheat. Also, there observed a synergy between applied fertilizers, particularly N, and S in increasing yield with each level and kind of fertilizer added, as evidenced by the existence of yield advantage at any given fertilizer level. Furthermore, the yield response correlates well with soil-test values, especially of N, OC, S and/or P. In the study, all 18 tested fields showed 100% full response to applied N. Similar to N, all study fields were low in available P, but about 78% showed response to applied P. In the case of S, however, 72.3% of the sites showed response to S, and there appeared to be a direct relationship. In general, there are strong indications that, the S response/deficiency which is observed in central HLs can be widespread, if such assessments were made across the country, and far into the out fields.

Based on the results obtained so far, therefore, the following recommendations can be made. Indeed, for resourceful farmers S demand can be met through the integration of S in a balanced fertilizer formula. For smallholding farmers, however, it is important to improve OM to sustainably build SOC stocks close to critical levels. It is also important to augment inorganic and organic fertilizers with local S sources (e.g., gypsum) to make advantage of integrative benefits and/or to economize fertilizer use.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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